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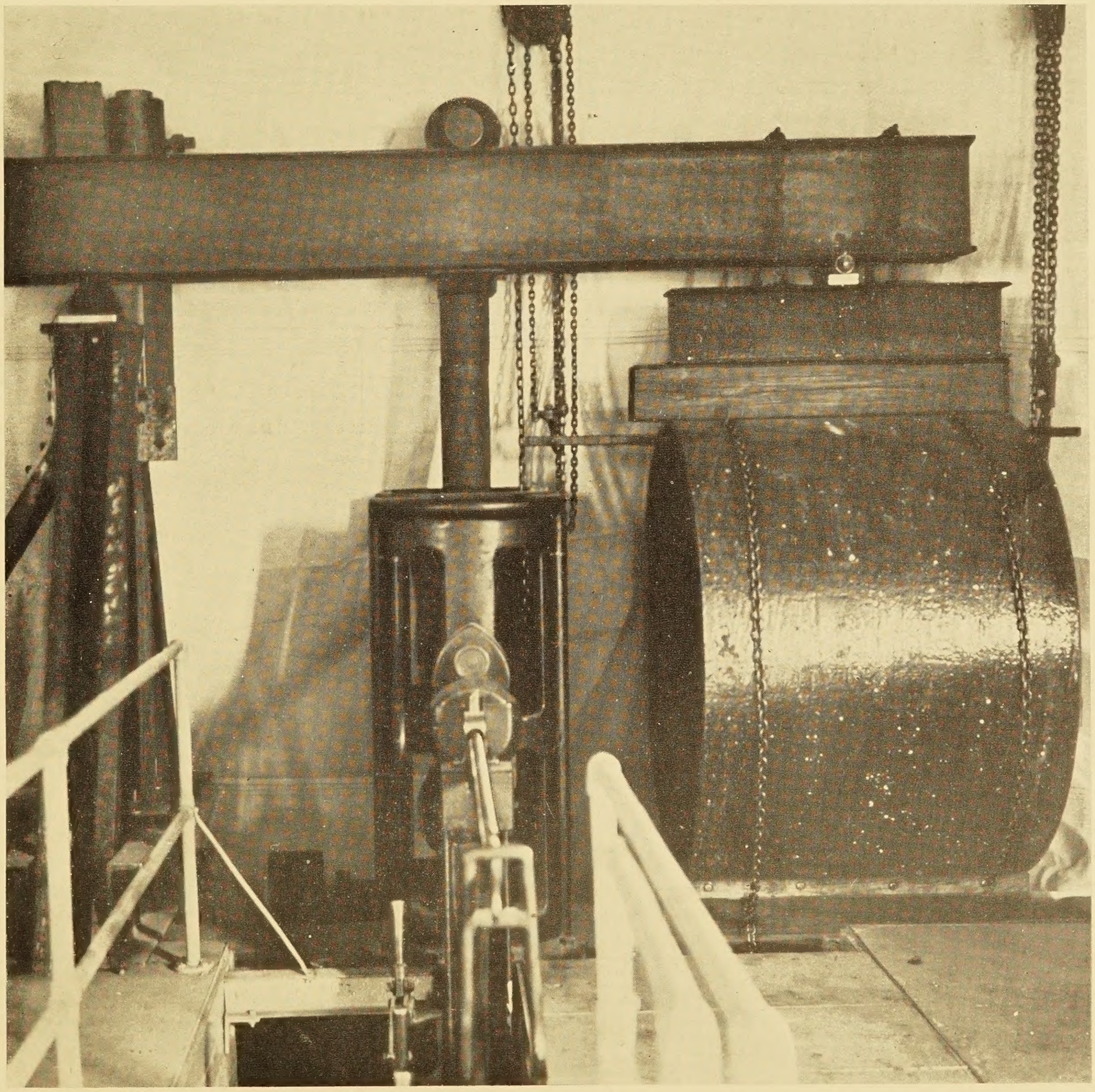

APPARATUS FOR TESTING CAST-IRON CULVERT PIPE

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The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done, the conclusions formulated must be considered as specifically pertinent only to described conditions

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STRENGTH TESTS OF CAST-IRON CULVERT PIPE

Reported by E. F. KELLEY, Chief, Division of Tests, and W. F. KELLERMANN, Associate Materials Engineer, United States Bureau of Public Roads

THE SPECIFICATIONS for cast-iron culvert pipe which are in common use in highway work are greatly lacking in uniformity, and show a wide range in the requirements for strength and thickness of metal for pipe which presumably are to be subjected to similar conditions of service.

INCONSISTENCIES FOUND IN SPECIFICATIONS

Of 36 State highway department specifications current in 1931, 2 required a minimum strength in the 3-edge bearing test but did not specify thickness of metal; 7 specified minimum thickness of metal but gave no strength requirements; and 27 specified both minimum strength and minimum shell thickness. In the specifications of the latter group the requirements for strength and shell thickness were not always consistent.

The minimum requirements for strength in the 3-edge bearing test ranged from 1,500 pounds per foot of diameter per linear foot of pipe (1,500 *D*) to 3,000 pounds per foot of diameter per linear foot of pipe (3,000 *D*). Fourteen States favored 1,500 *D* for all sizes of pipe, 4 States specified 1,800 *D*, 7 States required 2,000 *D* and 1 State required 3,000 *D*. Three States specified 1,500 *D* for pipe over 24 inches in diameter, and 2,000 *D* for pipe under 24 inches in diameter.

The diversity of the requirements for minimum shell thickness of smooth or plain cast-iron pipe is shown graphically in figure 1. Thus the minimum thickness for 12-inch pipe ranged from 0.31 to 0.54 inch and for 48-inch pipe the range was from 0.75 to 1.38 inch, a difference of nearly 100 percent. The influence of the standard requirements for cast-iron water pipe are also shown in figure 1, 2 States having specified for culvert pipe the thicknesses required for class A water pipe in the sizes up to and including 36-inch and 1 State specified the thickness required for the larger sizes of 42 inches and 48 inches.

The solid lines in figure 1 show the theoretical relationship between shell thickness and strength in the 3-edge bearing test, for smooth cast-iron pipe without hubs, for an assumed modulus of rupture of 35,000 pounds per square inch. This modulus of rupture is an approximate average figure for modulus of rupture obtained in tests of sand-cast pipe. The dotted lines show the theoretical thicknesses increased by 10 percent, an allowance suggested to provide for unavoidable inaccuracy in manufacture. It is interesting to observe that the minimum thicknesses commonly specified for the smaller sizes of pipes were generally in excess of those which would be required for a load of 3,000 *D* pounds per linear foot, while in the larger sizes the required thicknesses, in many cases, were below those which would be necessary to insure a load capacity of 2,000 *D*. It is believed that a strength of 2,000 *D* in the 3-edge bearing test is the minimum which should be required for cast-iron pipe for use in culverts, yet 21 States, in 1931, specified a minimum shell thickness of 0.69 inch for 36-inch pipe, which is too low to insure this strength in sand-cast pipe.

An example of the lack of relationship between requirements for strength and shell thickness was found in the specification of one State which required a minimum load of 1,500 *D* for pipe having the thickness of class A water pipe. Pipe of this weight is generally more than adequate for a load of 3,000 *D*. Another State specification required a minimum strength of 3,000 *D* but, for the larger sizes of pipe, specified minimum shell thicknesses insufficient for a load of 2,000 *D*.

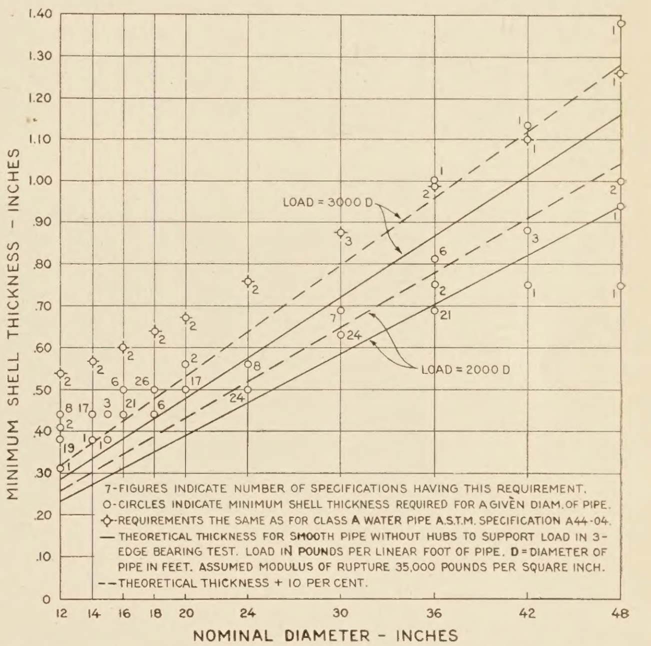

FIGURE 1.—RELATION BETWEEN MINIMUM SHELL THICKNESS AND DIAMETER OF SMOOTH CAST-IRON CULVERT PIPE AS SPECIFIED BY 34 STATES IN 1931.

The testing of cast-iron culvert pipe to determine compliance with specification requirements for strength is an expensive procedure, particularly if the ultimate strength of the test specimens is determined, thereby destroying the pipe. With a sufficient knowledge of the strength characteristics of commercial cast-iron pipe, as influenced by shell thickness and diamater, it should be possible to eliminate much of this expense and to accept pipe on the basis of thickness and weight more generally than has been customary in the past. It was largely on this account that the tests described in this report were undertaken, but the data which have been developed should also prove useful in indicating revisions which might be made in existing specifications in the interest of uniformity and consistency.

The culvert pipe tested were as follows:[1]

Smooth, sand-cast pipe, furnished by one manufacturer in sizes from 12- to 48-inch, and by another manufacturer in sizes from 12- to 36-inch.

[1] Acknowledgment is made to the United States Pipe and Foundry Co., the American Casting Co. and the Alabama Pipe Co. for the specimens of culvert pipe which were used in these tests.

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Smooth pipe cast by a centrifugal process in metal contact molds, in the sizes 12-, 16-, and 20-inch.

Spiral-corrugated pipe in sizes from 15- to 36-inch.

Ribbed pipe in the sizes 15-, 18-, and 24-inch.

In general three specimens of each size and type were tested. Six specimens of each size of smooth sand-cast pipe and of smooth centrifugally cast pipe were supplied, 3 specimens had bells or hubs and 3 had plain ends. There were 6 specimens of each size of spiral-corrugated pipe, 3 specimens representing the pipe section and 3 representing the cuff section. All specimens had a net length of approximately 3 feet, exclusive of the overlapping portion of end fittings. Some had been cast in this length and the others were cut from longer pipe. The smooth pipe with plain ends were cut from pipe which had been cast with hubs.

The spiral-corrugated pipe had a relatively thin shell which was cast in the form of spiral circumferential corrugations. Sections of pipe are fastened together by screwing one into the other. Since each section of pipe is of uniform diameter, the inner, or pipe section, is of slightly smaller diameter than the outer or cuff section.

respect to the position of the point or center of load application, for pipes with bell ends, that the various standard and tentative standard specifications differ and this is important since the position of the load has a considerable influence on the ultimate strength developed in the test.

Three positions of the load are used in various specifications:

(*a*) Load at the center of the upper bearing block.

(*b*) Load at the center of the laying-length of the pipe. The laying-length of pipe is the distance from the spigot end to the inside shoulder of the bell and therefore is a length intermediate between the length of the upper bearing block and the full length of the pipe, including the bell.

(*c*) Load at the center of the length of the pipe as shown at the top of figure 3. This position results in less eccentricity of load application than the other two and is required by the most recent specifications. This position of load, with a few exceptions which will be mentioned later, was used in these tests.

Position (*a*) is required by the A.S.T.M. (American Society for Testing Materials) Standard Specifications for Clay Sewer Pipe, C13-24 and A.S.T.M. Standard Specifications for Cement-Concrete Sewer Pipe, C14-24.

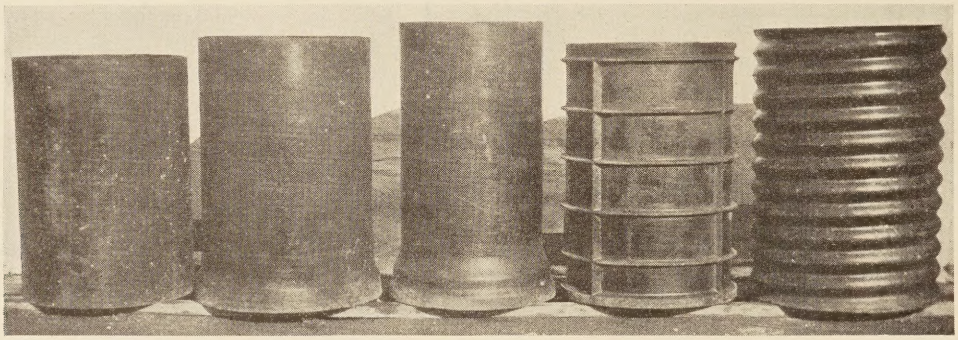

FIGURE 2.—REPRESENTATIVE SPECIMENS OF TYPES OF PIPE TESTED. SPECIMENS ARE (LEFT TO RIGHT) SMOOTH SAND-CAST PIPE, PLAIN END; SMOOTH SAND-CAST PIPE, BELL END; SMOOTH CENTRIFUGALLY CAST PIPE, BELL END; RIBBED PIPE; SPIRAL-CORRUGATED PIPE.

The ribbed pipe had a relatively thin shell reinforced by four longitudinal ribs, and by transverse ribs, the spacing of which varied somewhat with the size of the pipe.

Representative specimens of the different types of pipe are illustrated in figure 2.

SPECIFICATIONS VARY AS TO POSITION OF LOAD

All pipe were tested for strength in the 3-edge bearing test. This test has been used on sewer pipe and culvert pipe for a number of years and has become an accepted standard but it has not been completely standardized in one important respect. This is frequently overlooked and merits some discussion.

The general set-up for the test is shown in figure 3. The lower bearing consists of a rigid block to which are securely fastened two longitudinal wooden strips having vertical sides with the interior top corners rounded to a radius of approximately one half inch. The earlier specifications required that these strips be spaced 1 inch apart while the more recent ones provide that the space between them shall be not less than one half inch or more than 1 inch for each foot of nominal pipe diameter. The upper bearing, through which the load is applied, is a rigid wooden block. In the case of pipe with plain ends the upper and lower bearings extend the full length of the pipe while for pipe with bell ends the bearings extend from the spigot end to the point where the barrel begins to flare out to meet the bell. It is with

Position (*b*) is required by the 1926 Tentative Standard Specifications for Reinforced Concrete Culvert Pipe of the Joint Concrete Culvert Pipe Committee and by the Tentative Standard Methods of Sampling and Testing Highway Materials of the American Association of State Highway Officials as published in United States Department of Agriculture Bulletin No. 1216. Both of these have since been revised but the latter is still used to some extent.

Position (*c*) is required by the 1928 Tentative Standard Specifications of the Joint Concrete Culvert Pipe Committee; by the A.S.T.M. Tentative Standard Specifications for Reinforced-Concrete Culvert Pipe, C76-30T, which, in substance, are the same as the 1928 specifications of the Joint Committee; by the A.S.T.M. Tentative Standard Specifications for Reinforced-Concrete Pipe, C75-30T; and by the 1931 edition of the Tentative Standard Specifications for Highway Materials and Methods of Sampling and Testing of the American Association of State Highway Officials, which is a revision of Department of Agriculture Bulletin No. 1216.

The State specifications for making strength tests, discussed above, referred variously to A.S.T.M. Specifications C13-24 and C14-24 and to Bulletin No. 1216 of the Department of Agriculture. Some specified the 3-edge bearing test without describing it, others gave

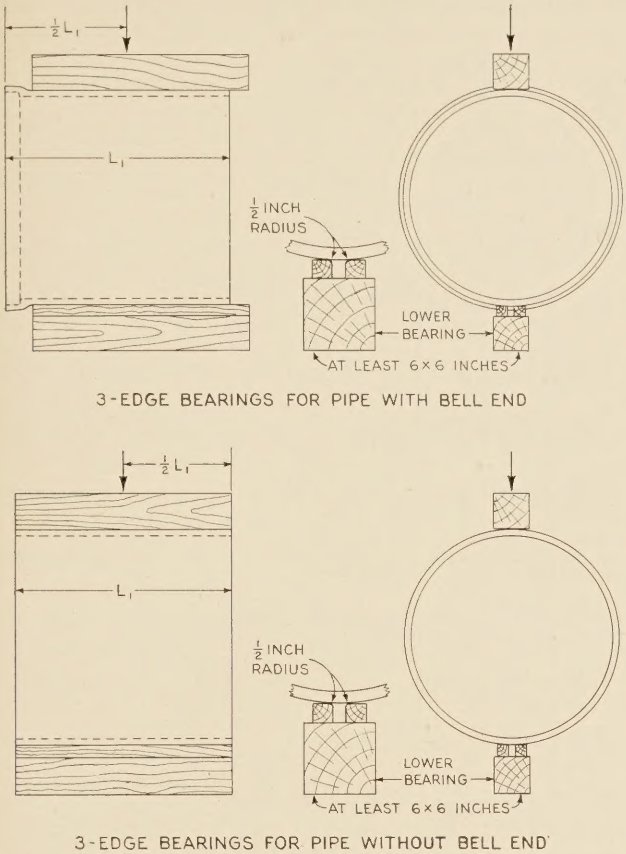

Figure 3.—Position of Bearings in Cast-iron Pipe Tests.

incomplete descriptions which did not define the position of load, another fairly large group required the test for strength to be made "in the manner prescribed by Committee C-4, American Society for Testing Materials." The latter is a particularly ambiguous requirement since, prior to 1932, all of the A.S.T.M. specifications to which reference has been made were under the jurisdiction of Committee C-4 and that, in addition to the 3-edge bearing test, these specifications also recognize the 2-edge bearing test and the sand-bearing test.

In conducting the 3-edge bearing test on the specimens included in this investigation, the distance between the longitudinal strips of the lower bearing was varied as shown in the following table:

Size of pipe	Distance between strips
Inches	*Inches*
12	1
15	1
16	1
18	1
20	2
24	2
30	2
36	3
42	3
48	3

The test load was applied to the upper bearing block at the center of the length of the pipe with the exception of four specimens of 12-inch pipe with bell ends. Three of these were sand-cast pipe furnished by manufacturer A and one was a specimen of centrifugally cast pipe (tables 1 and 3). In the case of the exceptions

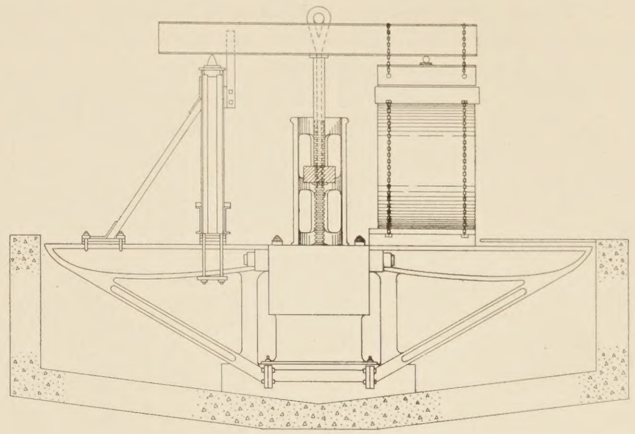

Figure 4.—Forty-Eight-Inch Pipe Set up in 200,000-Pound Testing Machine.

mentioned, the load was applied at the center of the length of bearing block and therefore was eccentric with respect to the center of length of the pipe.

TESTING APPARATUS DESCRIBED

Since a machine designed particularly for pipe testing was not available, the 3-edge bearing tests were made in a 200,000-pound universal testing machine having two extensions, or wings, attached to opposite sides and forming a part of the weighing table. The general arrangement of the testing apparatus is shown in figure 4. The cover page shows a 48-inch plain-end pipe ready for testing. The pipe was placed on one extension of the weighing table and on the opposite extension there was placed a vertical steel member of suitable height which served as a support for the loading beam and also as a counter weight. Two **I**-beams extending across the weighing table were supported on one side by a knife-edge bearing block on top of the vertical steel member and on the other side by a roller bearing which rested on the upper bearing block on the pipe. The load was applied through an eyebar and pin, the pin being supported by the **I**-beams at mid-span between the two bearings and the eyebar extending down through the movable head of the testing machine. A nut and washer on the lower end of the eyebar made contact with the movable head as it was lowered and thus transmitted load to the two bearings of the **I**-beams. With this arrangement the test load on the pipe was one half the load indicated on the weighing beam of the testing machine. During application of the load, the testing machine was run in low gear which corresponded to an idle crosshead speed of 0.05 inch per minute.

Straight bearing blocks of the same type were used on all types of pipe. This resulted in a much smaller area of contact on the special types of pipe than on the smooth pipe. On the corrugated pipe the applied load was concentrated on the upper surfaces of the corrugations and on the ribbed pipe the load was concentrated on the transverse ribs, the specimens being arranged for the test so that no load was applied to the longitudinal ribs. Figure 5 shows specimens of the corrugated pipe and the ribbed pipe with the bearing blocks which were used in testing them.

As has been stated, in general three specimens of each size and type of pipe were tested. On one pipe of each group of three, vertical deflections were measured during the loading tests with micrometer dials reading to 0.001 inch. Two such dials were used, one at each

TABLE 1.—*Smooth pipe, sand-cast, manufacturer A, 3-edge bearing, load applied at center of pipe unless otherwise noted*[1]

Type	Identification no.	Nominal size	Weight	Thickness at break[2]	Overall length	Laying length	Length of bearing	Load at failure	Supporting strength, pounds per foot of diameter per foot of laying length		Remarks
		Inches	*Pounds*	*Inches*	*Inches*	*Inches*	*Inches*	*Pounds*		*Average*	
Plain end	SP-12-1	12	172	0.45	36	36	36	25,550	8,520		
	2	12	170	.44	36	36	36	23,250	7,750	7,970	
	3	12	170	.44	36	36	36	22,950	7,650		
Bell end	SB-12-1	12	190	.49	38½	35¾	30	18,750	6,290		Load applied at center of bearing.
	2	12	190	.42	38½	35¾	30	18,950	6,360	6,340	Do.
	3	12	192	.46	38½	35¾	30	18,950	6,360		Do.
Plain end	SP-16-1	16	256	.55	35¾	35¾	35¾	24,250	6,100		
	2	16	250	.50	36	36	36	22,050	5,510	5,730	
	3	16	252	.51	36	36	36	22,310	5,580		
Bell end	SB-16-1	16	300	.54	38¼	35½	30	25,450	6,450		
	2	16	296	.52	38½	35½	30	24,200	6,140	6,490	
	3	16	304	.55	38¼	35¾	30	27,300	6,870		Broke through the bell.
Plain end	SP-20-1	20	346	.53	36¼	36¼	36¼	21,950	4,360		
	2	20	346	.50	35¾	35¾	35¾	19,500	3,930	3,880	
	3	20	314	.50	36	36	36	16,750	3,350		
Bell end	SB-20-1	20	404	.54	38½	35¾	30	25,600	5,150		Do.
	2	20	376	.50	38½	35¾	30	19,250	3,870	4,810	
	3	20	406	.58	38½	36	30	27,050	5,410		Do.
Plain end	SP-24-1	24	416	.54	35¾	35¾	35¾	14,300	2,400		
	2	24	432	.56	35¾	35¾	35¾	18,000	3,020	2,900	Crack in one side before test.
	3	24	424	.55	35¾	35¾	35¾	19,600	3,290		
Bell end	SB-24-1	24	540	.60	39	35¾	30	25,850	4,340		
	2	24	532	.57	39	35¾	30	23,500	3,940	3,980	
	3	24	538	.58	39	35¾	30	21,850	3,670		
Plain end	SP-30-1	30	644	.68	35¾	35¾	35¾	22,300	2,990		
	2	30	662	.74	35¾	35¾	35¾	21,200	2,850	2,860	
	3	30	646	.73	36	36	36	20,500	2,730		
Bell end	SB-30-1	30	770	.79	39	35¾	30	26,300	3,530		Broke through the bell.
	2	30	768	.73	39	35¾	30	22,900	3,070	3,320	Do.
	3	30	784	.75	39	36	30	25,250	3,370		Do.
Plain end	SP-36-1	36	882	.84	35¾	35¾	35¾	25,400	2,840		
	2	36	886	.79	36	36	36	16,450	1,830	3,000	Flaw in one end of break. Not included in average.
	3	36	1,000	.91	36	36	36	28,500	3,170		
Bell end	SB-36-1	36	1,070	.87	39	35¾	30	26,850	3,000		Broke through the bell.
	2	36	1,086	.85	39	35¾	30	31,600	3,530	3,330	Do.
	3	36	1,052	.82	39	35¾	30	30,850	3,450		Do.
Plain end	SP-42-1	42	1,300	1.06	36	36	36	35,950	3,420		
	2	42	1,340	1.00	36	36	36	31,300	2,980	3,120	
	3	42	1,230	.93	36	36	36	30,950	2,950		
Bell end	SB-42-1	42	1,520	1.00	39	36	30	39,900	3,800		Do.
	2	42	1,470	.92	39	36	30	36,550	3,480	3,650	Do.
	3	42	1,540	1.02	39	36	30	38,500	3,670		Do.
Plain end	SP-48-1	48	1,400	1.02	36	36	36	25,200	2,100		
	2	48	1,420	.90	36	36	36	22,300	1,860	1,970	
	3	48	1,400	.97	36	36	36	23,450	1,950		
Bell end	SB-48-1	48	1,695	1.00	39	36	30	31,950	2,660		Do.
	2	48	1,712	1.03	39	36	30	29,350	2,450	2,390	Do.
	3	48	1,680	.92	39	36	30	24,850	2,070		Do.

[1] Lower bearing blocks 1 inch apart for 12- and 16-inch pipe; 2 inches for 20-, 24-, and 30-inch pipe; 3 inches for 36-, 42-, and 48-inch pipe.
[2] Plain-end pipe—thickness is average of measurements at 10 points equally spaced along the crack. Bell-end pipe—thickness of barrel at spigot end.

end of the pipe. They were set 1 inch in from the ends of the pipe except when the specimens had bell ends, in which case the dial at the bell end was set 1 inch in from the inside shoulder of the bell. Figure 6 shows the position of the dials as they were set to measure the deflections of smooth pipe with plain ends. Deflections were observed for increments of load up to maximum values of from 10,000 to 15,000 pounds, after which the readings were discontinued. The results of the 3-edge bearing tests are shown in tables 1 to 5, inclusive.

These tables show the principal dimensions of each pipe tested and the load at failure. As a basis for comparison they also show the "supporting strength" in pounds per foot of diameter per foot of laying length. This supporting strength was determined by dividing the applied load by the product of the internal diameter and the laying length (in feet) and is hereafter referred to as the "strength."

LOCATION OF CRACK AT FAILURE AN INDICATION OF UNIFORMITY OF SPECIMEN

When an elastic ring is supported along the bottom element and a concentrated load is applied along the top element, as in the 2-edge bearing test, the maximum positive bending moments in the ring occur at the top and bottom, directly under the load and directly over the support. The bending moment in the ring decreases from a maximum positive value at the crown to a maximum negative value at the horizontal axis, passing through zero at a point the radius to which makes an angle with the vertical of approximately 40°.[2] The maximum positive bending moment at the crown is about 75 percent greater than the maximum negative moment at the horizontal axis.

In the 3-edge bearing test, as conducted on cast-iron pipe of ordinary dimensions, the bending moments are

[2] Tests of Cast-Iron and Reinforced Concrete Culvert Pipe, by Arthur N. Talbot. Bulletin No. 22, University of Illinois.

TABLE 2.—*Smooth pipe, sand-cast, manufacturer B, 3-edge bearing, load applied at center of pipe* [1]

Type	Identification no.	Nominal size	Weight	Thickness at break [2]	Over-all length	Laying length	Length of bearing	Load at failure	Supporting strength, pounds per foot of diameter per foot of laying length		Remarks
		Inches	*Pounds*	*Inches*	*Inches*	*Inches*	*Inches*	*Pounds*		*Average*	
Plain end	SP-12-1	12	172	0.51	36	36	36	24,600	8,200		
	2	12	161	.46	36	36	36	20,700	6,900	7,920	
	3	12	164	.48	36	36	36	25,950	8,650		
Bell end	SB-12-1	12	185	.50	39	36¼	35½	29,150	9,650		Broke through the bell.
	2	12	183	.42	39	36¼	35½	26,350	8,720	9,270	Do.
	3	12	183	.50	39	36¼	35½	28,500	9,430		Do.
Plain end	SP-18-1	18	226	.48	36	36	36	12,850	2,860		
	2	18	225	.44	36	36	36	14,600	3,240	3,390	
	3	18	235	.47	36	36	36	18,350	4,080		
Bell end	SB-18-1	18	275	.45	39	36	35	21,050	4,680		
	2	18	277	.43	39	36	35	14,750	3,280	3,940	
	3	18	276	.50	39	36	35	17,350	3,860		
Plain end	SP-24-1	24	405	.60	35	35	35	17,050	2,920		
	2	24	434	.62	35	35	35	21,300	3,650	3,340	
	3	24	406	.60	35	35	35	20,100	3,450		
Bell end	SB-24-1	24	474	.62	39	36	35	19,950	3,320		Do.
	2	24	471	.60	39	36	35	19,800	3,300	3,300	Do.
	3	24	464	.56	39	36	35	19,650	3,280		Do.
Plain end	SP-30-1	30	582	.70	34¾	34¾	34¾	19,650	2,710		
	2	30	574	.68	35	35	35	19,350	2,650	2,600	
	3	30	587	.68	35	35	35	17,750	2,430		
Bell end	SB-30-1	30	652	.62	39	36	35	21,650	2,890		
	2	30	665	.50	39	36	35	16,000	2,130	2,530	Do.
	3	30	654	.64	39	36	35	19,350	2,580		
Plain end	SP-36-1	36	[3] 940	.95	34½	34½	34½	30,450	3,530		
	2	36	[3] 940	.94	34½	34½	34½	29,250	3,390	3,460	
	3	36	[3] 940	.91	34½	34½	34½	23,550	[4] 2,730		
Bell end	SB-36-1	36	[3] 1,100	.92	39	36	34½	37,550	4,170		Do.
	2	36	[3] 1,100	.95	39	36	34½	32,100	3,570	3,870	Do.
	3	36	[3] 1,100	.92	39	36	34½	34,950	3,880		Do.

[1] Lower bearing blocks 1 inch apart for 12- and 18-inch pipe; 2 inches for 24- and 30-inch pipe; 3 inches for 36-inch pipe.
[2] Plain-end pipe—thickness is average of measurements at 10 points equally spaced along the crack. Bell-end pipe—thickness of barrel at spigot end.
[3] Approximate.
[4] Cracked before test, not included in average.

TABLE 3.—*Smooth pipe, centrifugally-cast, 3-edge bearing, load applied at center of pipe unless otherwise noted* [1]

Type	Identification no.	Nominal size	Weight	Thickness at break [2]	Over-all length	Laying length	Length of bearing	Load at failure	Supporting strength, pounds per foot of diameter per foot of laying length		Remarks
		Inches	*Pounds*	*Inches*	*Inches*	*Inches*	*Inches*	*Pounds*		*Average*	
Plain end	CP-12-1	12	165	0.42	36	36	36	25,950	8,650		
	2	12	168	.41	36	36	36	27,050	9,020	8,980	
	3	12	166	.42	36	36	36	27,800	9,270		
Bell end	CB-12-1	12	246	.44	40¾	36¼	34	31,475	10,420		
	2	12	250	.43	41	37	34	34,650	11,230	10,820	
	3	12	246	.43	40½	36¼	30	24,700	8,180		Load applied at center of bearing. Not included in average.
Plain end	CP-16-1	16	278	.51	36	36	36	32,300	8,080		
	2	16	280	.49	36	36	36	32,400	8,100	8,670	
	3	16	282	.58	36¼	36¼	36¼	39,650	9,840		
Bell end	CB-16-1	16	404	.51	40½	36	33	38,000	9,500		
	2	16	400	.51	40½	36	33	40,950	10,240	9,930	
	3	16	402	.51	40¾	36¼	33	40,460	10,040		
Plain end	CP-20-1	20	452	.63	36¼	36¼	36¼	32,350	6,430		
	2	20	440	.65	36½	36½	36½	37,950	7,490	6,830	
	3	20	446	.59	36¼	36¼	36¼	33,100	6,570		
Bell end	CB-20-1	20	570	.64	40½	36¼	33	44,500	8,840		
	2	20	572	.60	41	36½	33	40,950	8,080	8,640	
	3	20	580	.66	41	36¼	33	45,250	8,990		

[1] Lower bearing blocks 1 inch apart for 12- and 16-inch pipe; 2 inches apart for 20-inch pipe.
[2] Plain-end pipe—thickness is average of measurements at 10 points equally spaced along the crack. Bell-end pipe—thickness of barrel at spigot end.

substantially the same as in the 2-edge test. In the 3-edge test, as will be shown later, the moment at the crown is less than in the 2-edge test by an insignificant amount. Also in the 3-edge test the moment at the bottom of the pipe is slightly less than at the top.

Therefore, it is to be expected that a pipe which is exactly circular and of uniform thickness will crack, under the ultimate load in the 3-edge bearing test, along the upper element. Failure of the crack to develop in this position is evidence of nonuniformity, either in cross section or quality of metal. A slight nonuniformity may cause the pipe to break at the bottom rather than at the top but a crack along the horizontal axis evidences nonuniformity of considerable magnitude.

About 80 percent of the specimens of smooth sand-cast pipe furnished by manufacturer A broke at the top and the remainder broke at the bottom except one specimen which broke at a flaw near the bottom. Of the smooth sand-cast pipe of manufacturer B, one

TABLE 4.—*Spiral-corrugated pipe, 3-edge bearing, load applied at center of pipe* [1]

Type	Identification no.	Nominal size	Weight	Thickness at break [2]	Over-all length	Laying length	Length of bearing	Load at first crack	Load at failure	Supporting strength, pounds per foot of diameter per foot of laying length— At first crack	Average	At failure	Average
		Inches	*Pounds*	*Inches*	*Inches*	*Inches*	*Inches*	*Pounds*	*Pounds*				
Pipe	M-15-1	15	152	0. 27–0. 27	38¾	36	38¾	12, 700	15, 450	3, 390		4, 120	
	2	15	151	. 30– . 30	38¾	36	38¾	14, 600	15, 000	3, 890	3, 760	4, 000	4, 040
	3	15	152	. 28– . 28	38¾	36	38¾	15, 050	15, 050	4, 010		4, 010	
Cuff	F-15-1	15	157	. 24– . 33	38¾	36	38¾	12, 900	12, 900	3, 440		3, 440	
	2	15	153	. 22– . 32	38¾	36	38¾	13, 150	14, 700	3, 510	3, 120	3, 920	3, 630
	3	15	160	. 24– . 37	38¾	36	38¾	9, 050	13, 200	2, 410		3, 520	
Pipe	M-18-1	18	177	. 26– . 26	38¾	36	38¾	14, 250	14, 250	3, 170		3, 170	
	2	18	169	. 28– . 29	39	36	39	12, 500	13, 400	2, 780	2, 860	2, 980	2, 990
	3	18	168	. 24– . 28	38¾	36	38¾	11, 800	12, 650	2, 620		2, 810	
Cuff	F-18-1	18	192	. 20– . 30	38¾	36	38¾	12, 950	12, 950	2, 880		2, 880	
	2	18	187	. 25– . 34	38¾	36	38¾	12, 000	12, 600	2, 670	2, 680	2, 800	2, 770
	3	18	190	. 22– . 30	38¾	36	38¾	11, 250	11, 900	2, 500		2, 640	
Pipe	M-24-1	24	286	. 33– . 33	39½	36	39½	15, 800	15, 800	2, 630		2, 630	
	2	24	285	. 32– . 32	39½	36	39½	11, 300	12, 700	1, 880	2, 230	2, 120	2, 310
	3	24	286	. 32– . 32	39½	36	39½	13, 050	13, 150	2, 170		2, 190	
Cuff	F-24-1	24	285	. 32– . 33	39½	36	39½	12, 100	12, 300	2, 020		2, 050	
	2	24	289	. 35– . 40	39½	36	39½	15, 250	15, 400	2, 540	2, 350	2, 570	2, 370
	3	24	291	. 33– . 36	39½	36	39½	15, 000	15, 000	2, 500		2, 500	
Pipe	M-30-1	30	421	. 38– . 43	39½	36	39½	17, 350	20, 650	2, 310		2, 750	
	2	30	420	. 34– . 39	39½	36	39½	20, 250	21, 700	2, 700	2, 670	2, 890	2, 900
	3	30	425	. 38– . 38	39½	36	39½	22, 400	23, 050	2, 990		3, 070	
Cuff	F-30-1	30	467	. 45– . 55	39½	36	39½	21, 550	22, 450	2, 870		2, 990	
	2	30	481	. 37– . 49	39½	36	39½	19, 950	20, 950	2, 660	2, 710	2, 790	2, 900
	3	30	480	. 35– . 45	39½	36	39½	19, 500	21, 800	2, 600		2, 910	
Pipe	M-36-1	36	557	. 43– . 45	40¼	36	40¼	21, 400	21, 800	2, 380		2, 420	
	2	36	560	. 42– . 43	40¼	36	40¼	19, 150	22, 000	2, 130	2, 260	2, 440	2, 420
	3	36	557	. 43– . 44	40	36	40	20, 400	21, 700	2, 270		2, 410	
Cuff	F-36-1	36	646	. 45– . 57	40	36	40	24, 300	26, 600	2, 700		2, 960	
	2	36	636	. 41– . 56	40¼	36	40¼	23, 400	27, 000	2, 600	2, 690	3, 000	2, 930
	3	36	631	. 45– . 57	40	36	40	25, 000	25, 500	2, 780		2, 830	

[1] Lower bearing blocks 1 inch apart for 15- and 18-inch pipe; 2 inches for 24- and 30-inch pipe; 3 inches for 36-inch pipe.
[2] Thickness at break taken under load at end of pipe which cracked first. First value—thickness at bottom of corrugation. Second value—thickness at top of corrugation.

TABLE 5.—*Ribbed pipe, 3-edge bearing, load applied at center of pipe* [1]

Type	Identification no.	Nominal size	Weight	Thickness at break [2]	Distance from bell end to center line of first transverse rib	Distance between transverse ribs	Number of transverse ribs	Over-all length	Laying length	Load at first crack	Load at failure	Supporting strength, pounds per foot of diameter per foot of laying length— At first crack	Average	At failure	Average
		Inches	*Pounds*	*Inches*	*Inches*	*Inches*		*Inches*	*Inches*	*Pounds*	*Pounds*				
Bell end	R-15-1	15	150	0. 24–0. 79	5⅞	6⅞	5	36	34½	9, 850	11, 100	2, 740	2, 940	3, 090	3, 340
	2	15	150	. 33– . 91	5⅞	6⅞	5	36	34½	11, 250	12, 900	3, 130		3, 590	
Do	R-18-1	18	230	. 30–1. 05	5⅝	6 1/16	6	38½	37	19, 000	22, 650	4, 110		4, 900	
	2	18	228	. 28–1. 03	5⅝	6 1/16	6	38½	37	19, 650	19, 650	4, 250	4, 010	4, 250	4, 600
	3	18	228	. 28–1. 00	5⅝	6 1/16	6	38½	37	17, 000	21, 450	3, 680		4, 640	
Do	R-24-1	24	310	. 25–1. 20	6½	7 3/16	5	37½	36	13, 300	15, 000	2, 220		2, 500	
	2	24	306	. 33–1. 20	6½	7 3/16	5	37½	36	14, 850	18, 550	2, 470	2, 350	3, 090	2, 810
	3	24	303	. 30–1. 16	6½	7 3/16	5	37½	36	14, 200	17, 000	2, 370		2, 830	

[1] Lower bearing blocks 1 inch apart for 15- and 18-inch pipe; 2 inches for 24-inch pipe.
[2] First value—thickness of barrel at spigot end. Second value—total thickness of barrel and rib at first rib from spigot end.

third broke at the top and one third broke either at the bottom, or at the top and bottom approximately simultaneously. The remainder, except two in which the exact location of the crack was not determined, broke either at the side, or at the top and side, bottom and side, or top, bottom and side, simultaneously. About 65 percent of the specimens of spiral corrugated pipe broke at the top and the remainder, except three specimens in which the exact location of the crack was not determined, broke at the bottom. All specimens of the smooth, centrifugally cast pipe broke along the top indicating a greater uniformity in this group than in the other three which have been discussed. This is probably due to the method of manufacture which may be expected to result in a more uniform thickness of metal than sand-casting methods.

Ribbed pipe of the type tested is not of uniform cross section, and failure of the shell will not necessarily occur at the top. The bending moment on the horizontal axis through the center of the ring produces tensile stress in the outer fibers and the tensile stress produced in the small rib sections may be sufficient to produce initial failure at this point even though the bending moment is much less than at the crown, where the ribs are in compression. This type of failure actually occurred as was evidenced by crack development during the tests and by the fact that all of the eight specimens tested broke along both sides. Five of

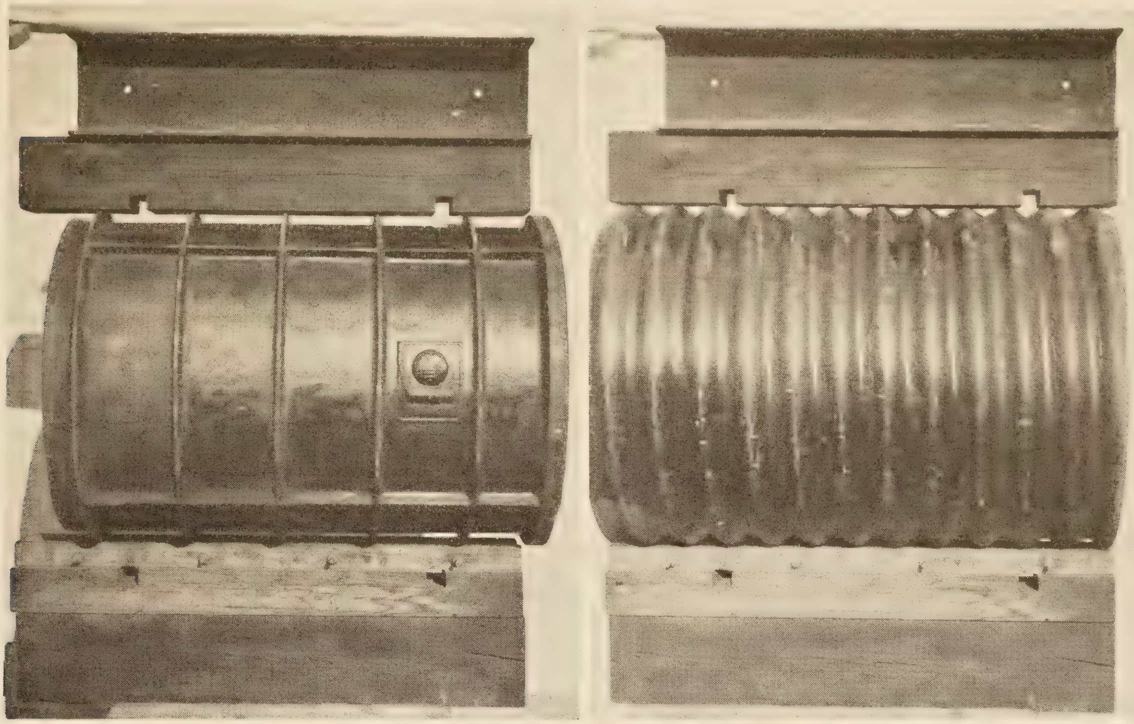

Figure 5.—Ribbed Pipe and Spiral-Corrugated Pipe with Bearing Blocks Used in 3-Edge Bearing Test.

them also broke at the top and one of these five also broke at the bottom.

In testing the smooth pipe with bell ends it was observed in numerous cases that, at failure, a crack developed in the body of the pipe without the development of a visible crack in the bell. The other cases, in which the crack developed throughout the length of the specimen, are indicated in tables 1 and 2.

INFLUENCE OF POSITION OF LOAD SHOWN IN TEST RESULTS

The test results for 12-inch pipe shown in tables 1 and 3 show that the position of the center of load application on the upper bearing block has an important influence on the strength developed by pipe with bell ends in the 3-edge bearing test. The tests of 12-inch pipe with bell ends reported in table 1 were all with the load applied at the center of the bearing block. The center of the load was 15 inches from the spigot end and the eccentricity of load, with respect to the center of length of the pipe, was 4¼ inches. The average strength of the bell-end pipe (6,340 D) was only 80 percent of the average strength of the 12-inch pipe with plain ends (7,970 D) on which the load was applied at the center of the pipe. In all the other tests of bell-end pipe shown in table 1 the load was applied at the center of the pipe and in every case the average strength of the bell-end pipe was greater than the average strength of plain-end pipe of corresponding size.

Bell-end pipe CB-12-3 (table 3) was tested with the point of load application at the center of the bearing block, the eccentricity with respect to the center of the pipe being 5¼ inches. The strength of this pipe was only 76 percent of the average strength of specimens CB-12-1 and CB-12-2 which were tested with the load in the center of the pipe. Also, the strength was only 91 percent of the average strength of the 12-inch pipe with plain ends. As in table 1, the average strength of all other bell-end pipe in table 3 is greater than the average strength of plain-end pipe of corresponding size. The influence of the position of the point of load application is also shown by the deflection measurements which will be discussed later.

It is apparent that the application of load at the center of the bearing block rather than at the center of length of the pipe subjects pipe with bell ends to an unduly severe load condition which results in an apparent lowering of their strength in the 3-edge bearing test. That it is not a fair test is evidenced by the failure of pipe loaded in this manner under lower loads than for failure of plain-end pipe of similar dimensions.

STRENGTH TESTS DISCUSSED

The average strength of bell-end specimens of the smooth, sand-cast pipe of manufacturer A (table 1),

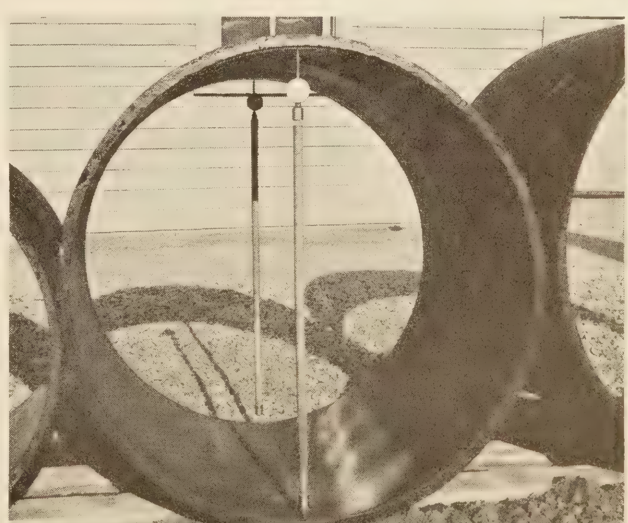

Figure 6.—Position of Micrometer Dials for Measuring Deflections of Smooth Pipe with Plain Ends.

TABLE 6.—*Vertical deflections of pipe*

Smooth sand-cast pipe, manufacturer A

Nominal diameter, inches	Total load of 3,000 pounds per foot of laying length: Bell-end pipe: Identification no.	Bell-end pipe: Deflections: Bell	Bell-end pipe: Deflections: Spigot	Bell-end pipe: Deflections: Average	Plain-end pipe: Identification no.	Plain-end pipe: Deflections [1]	Total load, 4,000 pounds per foot of laying length: Bell-end pipe: Deflections: Bell	Bell-end pipe: Deflections: Spigot	Bell-end pipe: Deflections: Average	Plain-end pipe: Deflections [1]	Plain-end pipe: $\frac{t}{d}$	Plain-end pipe: $\frac{\left(1+\frac{t}{d}\right)^3}{\left(\frac{t}{d}\right)^3}$
		Inches	Inches	Inches		Inches	Inches	Inches	Inches	Inches		
12	SB-12-3	0.013	0.121	[2] 0.067	SP-12-1	0.078	0.019	0.173	[2] 0.096	0.111	0.0369	22,200
16	SB-16-3	.038	.115	.076	SP-16-1	.116	.055	.161	.108	.165	.0340	28,100
20	SB-20-1	.066	.193	.130	SP-20-2	.198	.091	.270	.180	.285	.0244	74,000
24	SB-24-3	.081	.248	.164	SP-24-1	.344	.113	.344	.228	.497	.0220	100,200
30	SB-30-2	.119	.265	.192	SP-30-1	.316	.167	.371	.269	.454	.0225	93,900
36	SB-36-3	.110	.258	.184	SP-36-1	.343	.153	.356	.254	----------	.0232	85,800
42	SB-42-3	.127	.224	.176	SP-42-1	.307	.176	.309	.242	.430	.0252	67,300
48	SB-48-1	.196	.375	.286	SP-48-1	[3] .630	.272	.520	.396	----------	.0211	113,400

Smooth sand-cast pipe, manufacturer B

Nominal diameter, inches	Identification no. (bell-end)	Bell	Spigot	Average	Identification no. (plain-end)	Deflections [1]	Bell	Spigot	Average	Plain-end deflections [1]	$\frac{t}{d}$	$\frac{\left(1+\frac{t}{d}\right)^3}{\left(\frac{t}{d}\right)^3}$
12	SB-12-2	0.033	----------	----------	SP-12-3	0.066	0.047	----------	----------	0.094	0.0400	17,600
18	SB-18-3	.058	.314	.186	SP-18-2	.316	.081	0.437	0.259	.450	.0244	74,000
24	SB-24-2	.104	.252	.178	SP-24-2	.217	.144	.350	.247	.306	.0258	62,900
30	SB-30-2	.151	.417	.284	SP-30-2	.355	.212	.586	.399	.499	.0227	91,500
36	SB-36-2	.075	.214	.144	SP-36-1	.251	.104	.293	.198	.346	.0264	58,800

Smooth centrifugally cast pipe

Nominal diameter, inches	Identification no. (bell-end)	Bell	Spigot	Average	Identification no. (plain-end)	Deflections [1]	Bell	Spigot	Average	Plain-end deflections [1]	$\frac{t}{d}$	$\frac{\left(1+\frac{t}{d}\right)^3}{\left(\frac{t}{d}\right)^3}$
12	CB-12-2	0.016	0.073	0.044	CP-12-2	0.090	0.023	0.102	0.062	0.123	0.0331	30,400
16	CB-16-1	.034	.100	.067	CP-16-1	.098	.048	.139	.094	.138	.0311	36,400
20	CB-20-3	.036	.108	.072	CP-20-2	.103	.049	.146	.098	.143	.0322	32,900

Nominal diameter, inches	Spiral-corrugated pipe: Total load, 3,000 pounds per foot of laying length: Identification no.: Pipe	Identification no.: Cuff	Deflections [1]: Pipe	Deflections [1]: Cuff	Total load, 2,000 pounds per foot of laying length: Deflections [1]: Pipe	Deflections [1]: Cuff	Ribbed pipe: Identification no.	Total load, 3,000 pounds per foot of laying length: Deflections: Bell	Spigot	Average	Total load, 2,000 pounds per foot of laying length: Deflections: Bell	Spigot	Average
15	M-15-1	F-15-2	0.088	0.092	0.053	0.056	R-15-1	0.105	0.200	0.152	0.068	0.126	0.097
18	M-18-2	F-18-3	.168	[3] .168	.105	.103	R-18-2	.088	.130	.109	.056	.081	.068
24	M-24-3	F-24-3	.190	.186	.118	.116	R-24-3	.169	.215	.192	.108	.138	.123
30	M-30-2	F-30-3	.272	.237	.174	.154	----------	----------	----------	----------	----------	----------	----------
36	M-36-2	F-36-1	.327	.275	.212	.176	----------	----------	----------	----------	----------	----------	----------

[1] Average of deflections measured at each end of specimen. [2] Load applied at center of upper bearing block. [3] Extrapolated.

and the smooth, centrifugally cast pipe (table 3) which were loaded at the center of length was greater in all cases than the average strength of the corresponding specimens with plain ends. However, this was not always true of individual specimens.

For example: Bell-end pipe SB-20-2 developed a lower strength than the corresponding plain-end pipes SP-20-1 and SP-20-2; pipe SB-36-1 was not as strong as the plain-end specimen SP-36-3; and specimen SB-48-3 showed a lower strength than specimen SP-48-1. In the centrifugally cast pipe, bell-end specimen CB-16-1 developed a lower strength than the corresponding plain-end specimen CP-16-3. These apparent discrepancies may be attributed partly to differences in quality of metal and partly to differences in shell thickness due to unavoidable inaccuracies in manufacture.

In the smooth, sand-cast pipe of manufacturer B (table 2) the effect of the bell ends on strength is less pronounced than in the pipe of manufacturer A and the centrifugally cast pipe. This is probably due to differences in the design of the bells. (See fig. 7 for typical cross sections of 12-inch pipe.) There are more cases in which individual specimens with bell ends developed less strength than specimens of the same size with plain ends. In the case of the 24- and 30-inch pipe, even the average strength of the bell-end pipe was somewhat less than that of the pipe with plain ends.

Pipe with bell ends normally may be expected to develop a greater strength in the 3-edge bearing test, with the load applied at the center of length of the pipe, than pipe of the same size and dimensions with plain ends. However, these tests have shown that this differential in strength cannot always be expected on account of inaccuracy in manufacture and differences in quality of metal. It is indicated also that the amount of any strength differential which exists is influenced by the design of the bell. It is reasonable to assume that the differential is also dependent on the length of the specimen, being less for long pipe than for short ones. Since culvert pipe is furnished in lengths up to 12 feet, and it has been found in these tests that the 3-foot

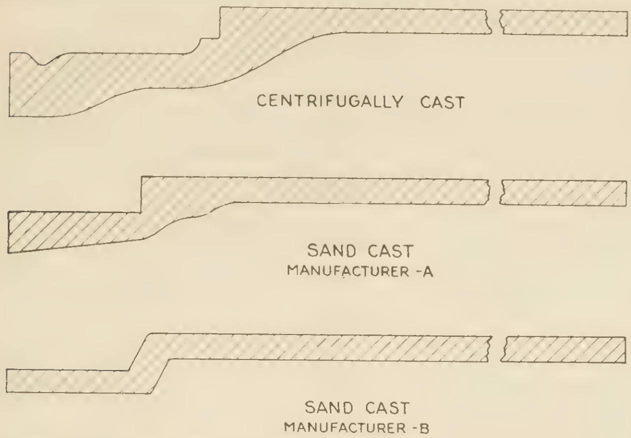

Figure 7.—Sections of Bell-End Pipe, Nominal Diameter 12 Inches.

specimens with bell ends did not consistently show a higher strength than pipe with plain ends, it is concluded that the design of cast-iron pipe to withstand the 3-edge bearing test may more safely be based on the results of tests on plain-end specimens than on tests of bell-end specimens.

In the tests of spiral corrugated pipe (table 4) and ribbed pipe (table 5) it was observed that the specimens cracked at a load which was generally, but not always, somewhat less than the ultimate load. Both the load at which the first crack developed and the ultimate load are reported although the former is considered to be more significant of the ability of the pipe to withstand the strength test.

The average strength at first crack of all sizes of corrugated pipe and ribbed pipe exceeded 2,000 pounds per foot of diameter per foot of length and only one specimen (M-24-2) developed a strength lower than this.

The supporting strength of spiral corrugated pipe is so dependent on the dimensions of the corrugations and that of ribbed pipe is so dependent on the size and location of the ribs that no general conclusions may be drawn from the results of these tests. The strengths reported are those developed by pipe of certain dimensions and design and it is not possible to derive from these results data applicable to pipe of different design or dimensions. The only conclusion which appears to be justified is that corrugated or ribbed pipe, similar in all respects to those included in these tests, may be expected to develop a strength in the 3-edge bearing test of at least $2{,}000D$ pounds per linear foot of laying length.

DEFLECTION OF PIPE DISCUSSED

Typical load-deflection curves obtained in these tests are shown in figure 8. The curves for all the other specimens are of the same general character varying only in the magnitude and relationship of deflections at a given load.

The significant data with respect to vertical deflections are given in table 6. This table shows the deflections of all specimens under a load of 3,000 pounds per foot of laying length, the maximum load at which readings on all pipe were available. For comparison, a second set of deflections under a different load is also given. For the smooth sand-cast and centrifugally cast pipe this load is 4,000 pounds per foot of laying length and for the spiral-corrugated and ribbed pipe it is 2,000 pounds per foot of laying length.

The smooth sand-cast pipe, SB-12-3, of manufacturer A was the only bell-end specimen on which deflection readings were obtained with the load applied at the center of the bearing block rather than at the center of the length of the pipe. Comment has already been made regarding the effect of this eccentric load application on the supporting strength and, as is to be expected, its influence on deflections is apparent. Comparing the deflections of specimen SB-12-3 under a load of either 3,000 or 4,000 pounds it will be noted that the deflection of the spigot end is about 56 percent greater than the deflection of the corresponding plain-end specimen, SP-12-1. For the 16- and 20-inch pipe of manufacturer A and the 18-inch pipe of manufacturer B, all of which were tested with the load applied at the center of length of the pipe, the deflections of the spigot end of the bell-end pipe are about the same as the deflections of the corresponding pipes with plain ends. Other things being equal, deflections are directly proportional to loads and therefore it is to be expected, as has already been shown to be the case, that an eccentricity of load application which causes the spigot end of a bell-end pipe to deflect much more than a plain-end pipe of the same metal and dimensions under symmetrical loading, will cause the bell-end pipe to fail at a lower load than the pipe with plain ends.

The data of table 6 and the curves of figure 8, which are all concave downward, show that the deflections increased at a somewhat greater rate than the corresponding loads.

A comparison of the average deflections of bell-end pipe with those of pipe with plain ends shows that in all cases, the presence of the bell resulted in a greater stiffness of pipe. However, only short lengths of pipe were tested. The increased stiffness is not always the same and this may be attributed to differences in the bells themselves.

Comparison of deflections of different types of pipe of the same size shows some differences in flexibility but it should not be concluded that these differences are necessarily inherent in the type itself. The type may have a considerable influence, as in the case of the spiral-corrugated pipe, which naturally is much stiffer than a smooth pipe of the same shell thickness, but the details of design are also of great importance. In general, pipe of the larger sizes show a greater flexibility than those of smaller size but this need not necessarily be the case. It should be remembered that deflection of a smooth pipe under a given load is dependent on three variables—diameter, shell thickness, and the modulus of elasticity of the metal.

The vertical deflection of smooth pipe with plain ends in the 2-edge bearing test [3] is given by the equation [4]—

$$\Delta y = 0.15\frac{Pr^3}{EI} \tag{2}$$

where

Δy = vertical deflection, in inches,
P = load, in pounds,
r = radius of center line of shell, in inches,
E = modulus of elasticity, in pounds per square inch,
I = moment of inertia of a longitudinal element of the shell, in inches^4.

[3] As will be shown in the discussion of modulus of rupture of pipe, this test may be considered, for all practical purposes, to be the same as the 3-edge bearing test.
[4] Tests of Cast-Iron and Reinforced Concrete Culvert Pipe, by Arthur N. Talbot, Bulletin No. 22, University of Illinois.

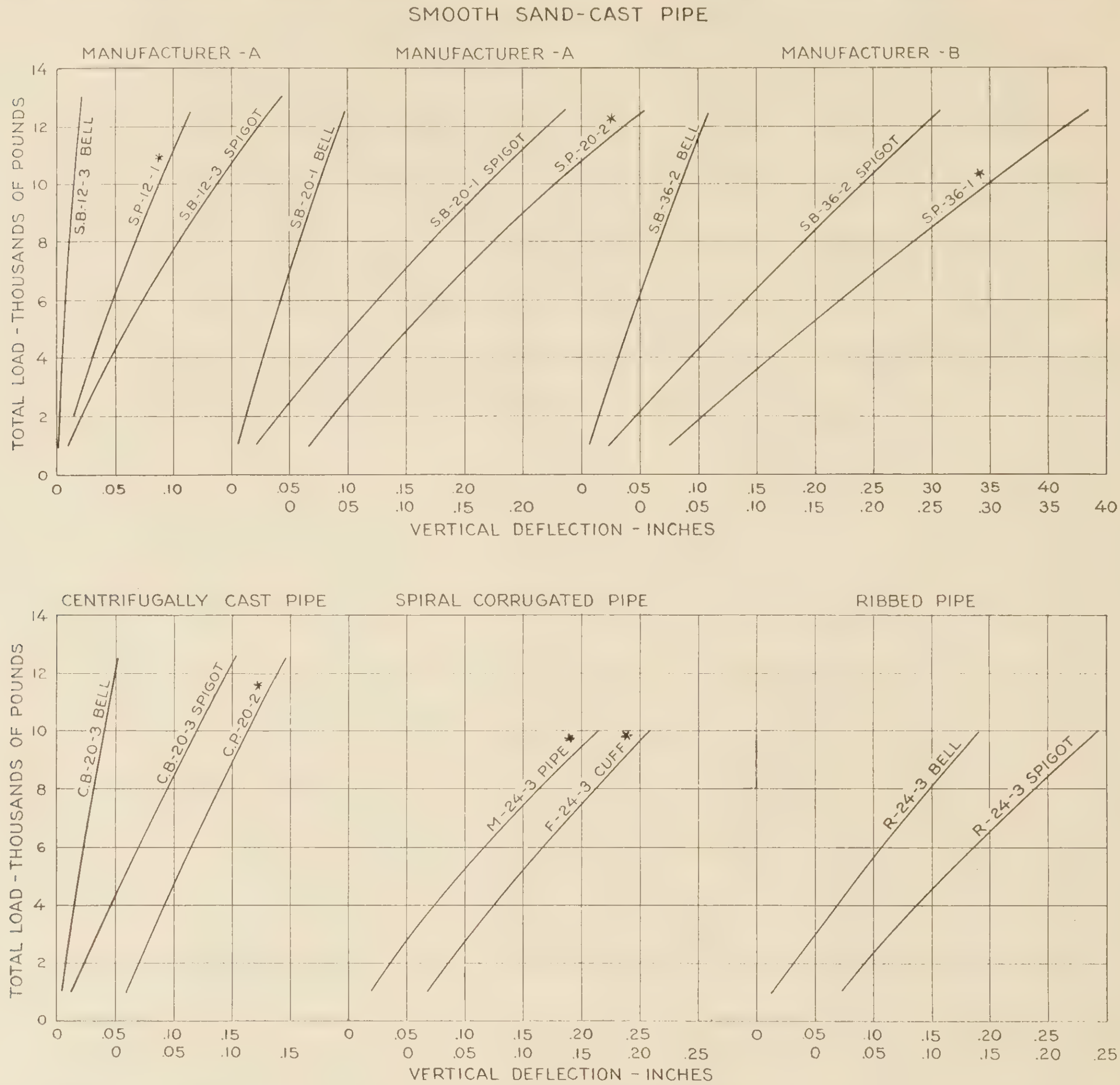

Figure 8.—Typical Load-Deflection Curves. An Asterisk Following the Serial Number Indicates Deflections Are Averages of Measurements at Each End of Pipe.

This equation is applicable to pipe of constant section and constant modulus of elasticity. Cast-iron pipes, due to unavoidable inaccuracies in manufacture, are not accurately uniform in cross section and the modulus of elasticity of cast iron is not a constant. However, the formula is useful as a basis of comparison and, as has been pointed out by Talbot, may be used somewhat empirically.

By making suitable substitutions, equation 1 may be reduced to the form—

$$\Delta y = \frac{0.225P\left(1+\frac{t}{d}\right)^3}{Eb\left(\frac{t}{d}\right)^3} \qquad (2)$$

where

t = shell thickness, in inches,
d = inside diameter of pipe, in inches,
b = length of pipe, in inches.

For convenience equation 2 may be written—

$$\Delta y = \frac{0.225P}{Eb} \qquad (3)$$

where

$$K = \frac{\left(1+\frac{t}{d}\right)^3}{\left(\frac{t}{d}\right)^3}$$

Thus, for constant value of load, modulus of elasticity, and length of pipe, there is a straight-line relationship between deflections and values of K.

Values of $\frac{t}{d}$ and K for the smooth pipe with plain ends are given in table 6 and, in figure 9, these values of K have been plotted against the corresponding observed deflections. The values of t used in computing K are the average thicknesses as measured along the crack in the pipe and given both in tables 1, 2, and 3 and tables 7, 8, and 9. Values of d are the average inside diameters as given in tables 7, 8, and 9. Since the pipe shells did not have a constant thickness and were not always exactly circular in cross section, these values of t and d are not necessarily the true values which should be used in computing deflections. However, they are the best figures available and it is believed that there are no departures from true values of sufficient magnitude to introduce errors of consequence in this discussion. Therefore, the deviations of the plotted points from the straight-line relationships shown in figure 9 are due primarily to deviations of the moduli of elasticity from the average modulus at this particular load.

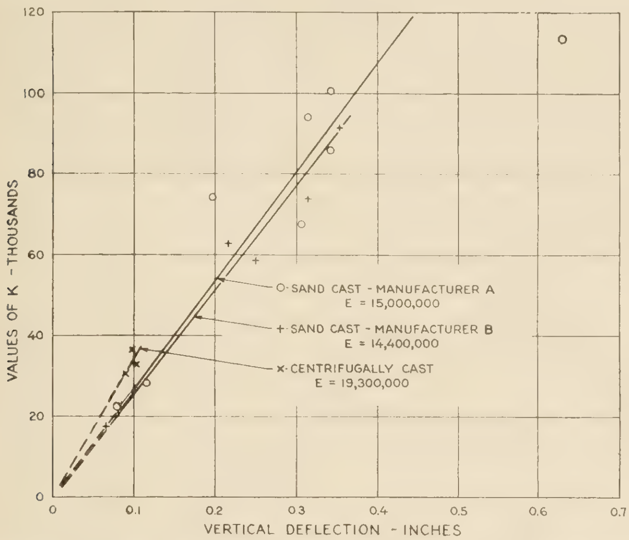

FIGURE 9.—RELATIONSHIP BETWEEN VERTICAL DEFLECTIONS IN 3-EDGE BEARING TEST AND VALUES OF K FOR SMOOTH CAST-IRON PIPE WITH PLAIN ENDS BASED ON A LOAD OF 3,000 POUNDS PER LINEAR FOOT OF PIPE.

The average straight-line relationships between vertical deflections and values of K, for the three groups of pipe, correspond to moduli of elasticity of 14,400,000, 15,000,000, and 19,300,000 pounds per square inch, respectively, for the sand-cast pipe of manufacturer B, the sand-cast pipe of manufacturer A and the centrifugally cast pipe. This order of values of moduli is not in agreement with the order of values shown by the strip tests which will be described later. The average values of moduli of elasticity, as determined by tests on strips, are lowest for the sand-cast pipe of manufacturer A and highest for the centrifugally cast pipe.

While there is a fairly large difference between the average moduli of the sand-cast pipe and that of the centrifugally cast pipe, it is apparent that, for the smooth pipe included in this study, the magnitude of the vertical deflections under a given load in the 3-edge bearing test was influenced more by variations in the ratio of shell thickness to diameter than by variations in the modulus of elasticity of the metal.

MODULUS OF RUPTURE OF PIPE STUDIED

The load capacity of cast-iron pipe in the 3-edge bearing tests is influenced by the diameter of the pipe, the thickness of the shell, and the strength of the metal, and it is impossible to study the influence of any one of these variables without a knowledge of the other two. In any given case, the first two variables may be determined by measurement. As a measure of the third variable, the strength of the metal, the modulus of rupture, computed from the results of tests, is useful.

The 2-edge or "knife-edge" bearing test is the same as the 3-edge bearing test except that in the former the lower bearing consists of a single strip instead of two strips as in the latter. Thus, in the 2-edge test the specimen is loaded through the upper and lower elements which are in a vertical plane through the longitudinal axis of the pipe. It has been shown [5] that in a thin elastic ring loaded in this manner the maximum moment occurs under the load and is given by the equation

$$M_2 = \frac{Pr}{\pi} \qquad (4)$$

where

M_2 = bending moment, in inch-pounds,
P = load, in pounds,
r = radius of center line of ring, in inches.

It has also been shown [5] that, for a thin, elastic ring in the 3-edge bearing test, the moment under the load is given by the equation—

$$M_3 = \frac{Pr}{2\pi}\left(1 + \sqrt{1 - \frac{a^2}{r^2}} + \frac{a}{r}\alpha - \frac{a^2}{r^2}\right) \qquad (5)$$

where

M_3 = bending moment in inch-pounds,
P = load in pounds,
r = radius of center line of ring in inches,
a = one half the distance, between the lower bearing strips in inches,
α = angle, in radians, whose sine equals $\frac{a}{r}$.

Equation 4 gives calculated bending moments somewhat larger than those given by equation 5 but the difference is so slight as to be negligible for pipe having the dimensions of those which are under discussion. For example, for a pipe having an inside diameter of 12 inches and a shell thickness of one half inch, the moment for the 2-edge bearing exceeds that for the 3-edge bearing with lower bearings 1 inch apart, by less than 1 percent. The same is true for a pipe having an inside diameter of 48 inches, a shell thickness of 1 inch, and the lower bearings in the 3-edge test spaced 4 inches apart. Since this is the case, it will be sufficiently accurate, and more convenient on account of its greater simplicity, to use the equation for the 2-edge bearing test in calculating the modulus of rupture for pipe tested in the 3-edge test.

The modulus of rupture may be calculated from the usual flexure formula—

$$R = \frac{Mc}{I} \qquad (6)$$

where

R = modulus of rupture, or computed fiber stress in pounds per square inch,
M = bending moment in inch-pounds,
c = distance from neutral axis to extreme fiber in inches,
I = moment of inertia of the section (longitudinal element of the shell), in inches [4].

Combining equations 4 and 6,

$$R = \frac{Prc}{\pi I}$$

[5] Tests of Cast-Iron and Reinforced Concrete Culvert Pipe, by Arthur N. Talbot, Bulletin No. 22, University of Illinois. Experimental and Mathematical Analyses of Drain Tile Testing and New Test Bearing, by Dalton G. Miller and Joseph A. Wise, Technical Bulletin 52, University of Minnesota Agricultural Experiment Station.

Let

d = inside diameter of pipe in inches,

t = shell thickness in inches,

b = length of pipe in inches.

Then

$$R = \frac{0.955\,P(d+t)}{bt^2} \qquad (7)$$

When

b = 12 inches and P = load in pounds per linear foot of pipe,

$$R = \frac{.0796P(d+t)}{t^2} \qquad (8)$$

The flexure formula, equation 6, is based on the assumptions that the modulus of elasticity is a constant and that the fiber stress is within the elastic limit of the material. For cast-iron at the breaking load these assumptions are not fulfilled and therefore the modulus of rupture, as given by equations 7 or 8, is not the true stress in the outer fiber. However, as with other materials, the calculated modulus of rupture of cast-iron is a useful measure of the strength of the material at its ultimate load.

DESIGN DATA PRESENTED

Values for the moduli of rupture of the smooth pipe with plain ends (described in tables 1, 2, and 3) have been calculated from equation 8 and the results are given in tables 7, 8, and 9. These tables also give the average inside diameters of the pipe, which generally vary somewhat from the nominal diameters; and the maximum and minimum, as well as the average, thickness of shell at the break. In the computations, the average inside diameter was substituted for d and the average shell thickness at the break for t.

TABLE 7.—*Breaking load and moduli of rupture of smooth sand-cast pipe with plain ends of manufacturer A*

Identification no.	Nominal diameter	Average inside diameter	Shell thickness at break			Breaking load	Modulus of rupture	Average	Deviation from grand average
			Maximum	Minimum	Average[1]				
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Lb. per foot*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Percent*
SP-12-1	12	12.2	0.47	0.44	0.45	8,520	42,300		13.1
2	12	12.2	.46	.41	.44	7,750	40,300	40,800	7.8
3	12	12.2	.46	.41	.44	7,650	39,700		6.1
SP-16-1	16	16.2	.58	.52	.55	8,140	35,900		4.0
2	16	16.2	.52	.48	.50	7,350	39,100	37,700	4.5
3	16	16.2	.54	.49	.51	7,440	38,000		1.6
SP-20-1	20	20.5	.54	.52	.53	7,270	43,300		15.8
2	20	20.5	.52	.47	.50	6,550	43,700	41,400	16.8
3	20	20.5	.51	.50	.50	5,580	37,300		.3
SP-24-1	24	24.5	.55	.53	.54	4,800	32,800		12.3
2	24	24.5	.59	.53	.56	6,040	38,400	38,200	2.7
3	24	24.5	.57	.53	.55	6,580	43,400		16.0
SP-30-1	30	30.2	.71	.65	.68	7,490	39,800		6.4
2	30	30.2	.77	.72	.74	7,120	32,000	34,400	14.4
3	30	30.1	.76	.71	.73	6,830	31,500		15.8
SP-36-1	36	36.2	.85	.82	.84	8,530	35,600	34,600	4.8
3	36	36.0	.93	.88	.91	9,500	33,700		9.9
SP-42-1	42	42.0	1.08	1.04	1.06	11,980	36,500		2.4
2	42	42.0	1.01	.99	1.00	10,430	35,700	37,700	4.5
3	42	42.1	.96	.92	.93	10,320	40,800		9.1
SP-48-1	48	48.4	1.05	1.00	1.02	8,400	31,800		15.0
2	48	48.5	.93	.87	.90	7,430	36,100	33,500	3.5
3	48	48.5	.99	.95	.97	7,820	32,700		12.6
Grand av.							37,400		8.7

[1] Average of thickness at 10 equally spaced points along the crack.

TABLE 8.—*Breaking load and moduli of rupture of smooth sand-cast pipe with plain ends of manufacturer B*

Identification no.	Nominal diameter	Average inside diameter	Shell thickness at break			Breaking load	Modulus of rupture	Average	Deviation from grand average
			Maximum	Minimum	Average[1]				
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Lb. per foot*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Percent*
SP-12-1	12	11.9	0.59	0.44	0.51	8,200	31,100		9.3
2	12	11.9	.50	.42	.46	6,900	32,100	33,500	6.4
3	12	12.0	.51	.44	.48	8,650	37,300		8.7
SP-18-1	18	18.0	.55	.43	.48	4,280	27,300		20.4
2	18	18.0	.47	.42	.44	4,870	36,900	34,900	7.6
3	18	17.9	.52	.44	.47	6,120	40,500		18.1
SP-24-1	24	23.8	.63	.55	.60	5,850	31,500		8.2
2	24	24.0	.64	.57	.62	7,300	37,200	35,400	8.5
3	24	24.0	.61	.60	.60	6,890	37,500		9.3
SP-30-1	30	30.0	.75	.59	.70	6,780	33,800		1.5
2	30	30.0	.70	.65	.68	6,630	35,000	33,600	2.0
3	30	30.0	.72	.59	.68	6,090	32,100		6.4
SP-36-1	36	36.0	1.03	.88	.95	10,590	34,500	34,200	.6
2	36	36.0	.99	.82	.94	10,170	33,800		1.5
Grand av.							34,300		7.7

[1] Average of thickness at 10 equally spaced points along the crack.

TABLE 9.—*Breaking load and moduli of rupture of smooth centrifugally cast pipe with plain ends*

Identification no.	Nominal diameter	Average inside diameter	Shell thickness at break			Breaking load	Modulus of rupture	Average	Deviation from grand average
			Maximum	Minimum	Average[1]				
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Lb. per foot*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Percent*
CP-12-1	12	12.4	0.43	0.42	0.42	8,650	50,000		4.4
2	12	12.4	.42	.40	.41	9,020	54,700	52,800	4.6
3	12	12.4	.43	.41	.42	9,270	53,600		2.5
CP-16-1	16	16.4	.53	.50	.51	10,770	55,700		6.5
2	16	16.2	.50	.49	.49	10,800	59,700	55,600	14.1
3	16	16.0	.65	.52	.58	13,130	51,500		1.5
CP-20-1	20	20.2	.63	.62	.63	10,710	44,700		14.5
2	20	20.2	.68	.63	.65	12,480	49,000	48,600	6.3
3	20	20.2	.61	.57	.59	10,960	52,100		0.4
Grand av.							52,300		6.1

[1] Average of thickness at 10 equally spaced points along the crack.

In comparing the average moduli of rupture of the three groups of specimens shown in these tables, the relatively high modulus of the centrifugally cast pipe is noteworthy. The pipe of this group have an average modulus of rupture of 52,300 pounds per square inch as compared with 37,400 pounds per square inch for the sand-cast pipe of manufacturer A and 34,300 pounds per square inch for the sand-cast pipe of manufacturer B. These results, as well as those of the strip tests to be described later, show that the centrifugally cast metal in these specimens is unquestionably of materially higher strength than the metal in the specimens which were cast in sand molds in accordance with common foundry practice.

The consistency of the values of modulus of rupture developed by individual specimens in each of the three groups is considered to be reasonably good, the average deviations being 8.7 percent, 7.7 percent, and 6.1 percent, respectively, for the sand-cast pipe of manufacturer A, the sand-cast pipe of manufacturer B, and the centrifugally cast pipe. The relatively low average deviation for the centrifugally cast pipe may be indicative of a more uniform product but this figure is established by fewer specimens than in the other groups and the maximum deviations for individual specimens of centrifugally cast pipe are not greatly lower than are those for individual specimens of the sand-cast pipe of manufacturer A.

It is important to note that, in spite of the reasonably low average deviations, the calculated moduli of rupture of individual specimens vary through a rather wide range in all three groups. For the sand-cast pipe of manufacturer A the modulus of rupture varies from a minimum value of 31,500 pounds per square inch to a maximum of 43,700 pounds per square inch and the maximum deviation from the average is 16.8 percent. The variation for the sand-cast pipe of manufacture B is from 27,300 to 40,500 pounds per square inch with a maximum deviation of 20.4 percent, while for the centrifugally cast pipe the range is from 44,700 to 59,700 pounds per square inch with a maximum deviation of 14.5 percent.

The moduli of the sand-cast pipe of manufacturer A and of the centrifugally cast pipe show a general trend, though not a very marked or consistent one, toward lower values with increasing thicknesses of shell. The moduli developed by the sand-cast pipe of manufacturer B appear to be independent of shell thickness.

A knowledge of the modulus of rupture of cast-iron pipe, which may be expected in any particular case, is useful in designing pipe to resist a given load in the 3-edge bearing test, or in predicting the approximate load which pipe of a given thickness and known quality of metal will support.

The strength of pipe in the 3-edge test is commonly expressed in pounds per linear foot of pipe per foot of pipe diameter. Thus, pipe is said to have a strength of 2,000 D pounds per linear foot, D being the nominal inside diameter of the pipe in feet. In this connection it is convenient to transpose equation 8 into another form.

In this equation—

P = load in pounds per linear foot of pipe,
d = inside diameter of pipe, in inches,
Let L = load in pounds per linear foot of pipe per foot of pipe diameter.

Then $P=\frac{Ld}{12}$

Substituting in equation 8,

$$R=\frac{.0796\ Ld\ (d+t)}{12t^2}$$

and

$$L=\frac{12\ Rt^2}{.0796\ d\ (d+t)}=\frac{12\ R\frac{t^2}{d^2}}{.0796\left(1+\frac{t}{d}\right)} \qquad (9)$$

Thus, for any given value of load, L, and modulus of rupture, R, the ratio of shell thickness to diameter $\frac{t}{d}$ is a constant.

The curves of figure 10 are based on calculations made with equation 9 and may be used to determine the shell thickness of smooth cast-iron pipe for any required strength and assumed modulus of rupture, or to predict the approximate strength of pipe when the ratio, $\frac{t}{d}$, and the approximate modulus of rupture is known.

In designing pipe for strength by the use of equation 9 consideration should be given, in the selection of the value of R to be used, to the range in values of modulus of rupture which may be expected in pipe manufactured to meet the design requirements. Also, some allowance in shell thickness should be made as a safeguard against unavoidable inaccuracies in the manufacture of the pipe. An arbitrary increase in the theoretical thickness given by equation 9, of not less than 10 percent is suggested.

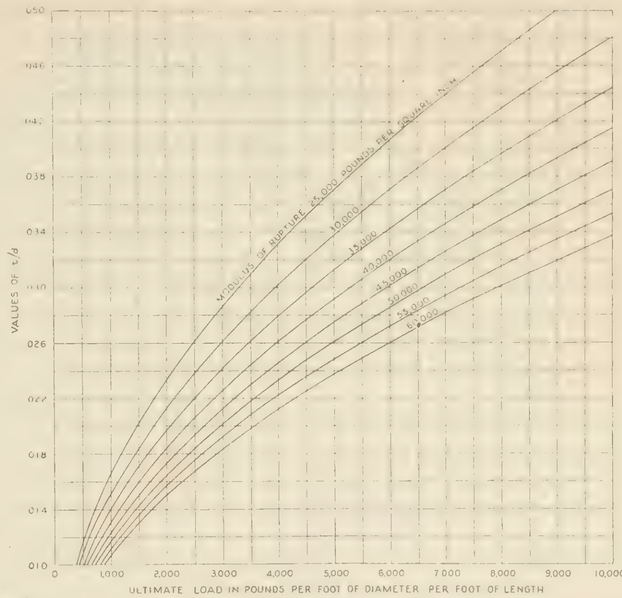

Figure 10.—Theoretical Relation Between Ultimate Load in the 3-Edge Bearing Test and the Ratio of Shell Thickness to Inside Diameter for Smooth Cast-Iron Pipe with Plain Ends.

BENDING TESTS MADE ON STRIPS CUT FROM PIPE

Some specifications for cast-iron pipe, notably those of the Federal Government, require bending tests on small machined strips cut from sample pipe, and provide limiting values for the modulus of rupture of such strips and for the secant modulus of elasticity at the breaking load.

For example, the following requirements are quoted from Federal Specification WW-P-421 for Cast-Iron Water Pipe (Bell and Spigot):

F-4a. From each 300 lengths of pipe, or fraction thereof, of each size in the contract or order, one length of pipe shall be selected by the inspector before coating. From each sample pipe there shall be cut and machined one test strip 12 inches long, 0.50 inch deep, and the full thickness of the shell in width. This shall be tested as a beam (with machined surfaces top and bottom) on supports 10 inches apart with load applied at two points 3⅓ inches from the supports. The strip shall be accurately calipered at point of rupture and stress calculated by the formula

$$S=\frac{PLc}{6I},\ \text{or for the above specimen}\ S=\frac{40P}{b}$$

F-4b. The secant modulus of elasticity at the breaking load shall be calculated by the formula

$$E=\frac{23PL^3}{1296Iy},\ \text{or for the above specimen}\ E=S\frac{42.6}{y}$$

In these formulas,
S = modulus of rupture,
E = modulus of elasticity,
P = total load,
L = length of span,
c = distance to extreme fiber,
I = moment of inertia,
b = width of specimen (thickness of pipe),
d = depth of specimen,
y = center deflection at load P.

It has been suggested that the modulus of rupture developed by these small test specimens might serve as an index of the modulus of rupture developed by

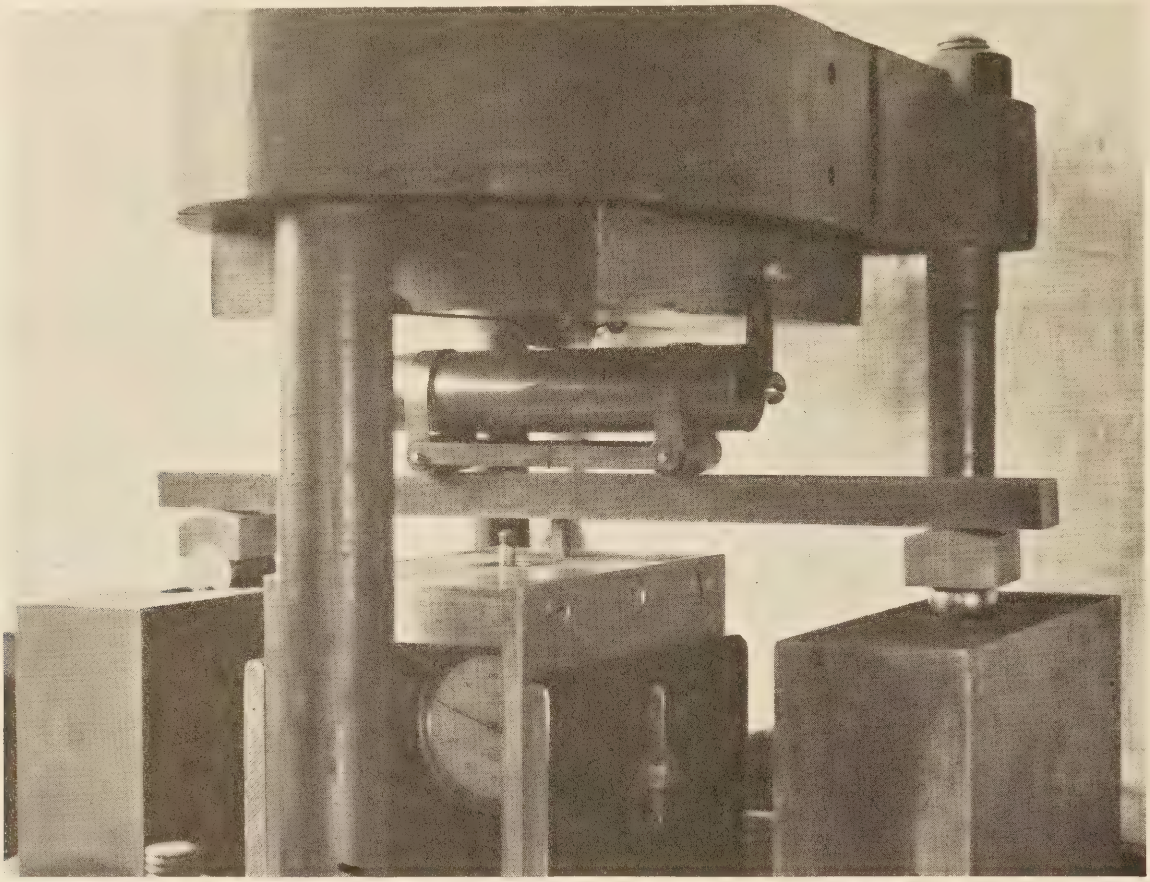

FIGURE 11.—APPARATUS FOR TESTING SMALL STRIPS OF METAL CUT FROM CAST-IRON PIPE.

the specimens of pipe from which the strips are cut in the 3-edge bearing test. The advantages to be gained by testing small strips of metal rather than full-size specimens of pipe, both from the standpoint of convenience and economy, are manifest. In order to determine the suitability of the strip test as a measure of the supporting strength of pipe, a complete series of tests was made on strips cut from all the smooth pipe with plain ends which are listed in tables 7, 8, and 9.

The strips were taken from the pipe which had been broken in the strength tests and were machined and tested in accordance with the specifications quoted above. A 20,000-pound universal testing machine, converted to 2,000-pound capacity for these tests, was used for applying the loads, the moving head being operated at an idle crosshead speed of 0.03 inch per minute.

The loads were applied to the strips at the third points through a system of cylindrical rollers and the specimen was supported by blocks with line-bearings which in turn were supported by a cylindrical bearing at one end and a spherical bearing at the other. A view of the testing apparatus is shown in figure 11.

The cross-sectional dimensions of the specimen at the point of rupture were determined by measurements with micrometer calipers. The modulus of rupture was computed from these dimensions and the load at failure. The pitch coating and any sand adhering to the surface of the metal was removed from the strips by grinding before they were tested.

The deflections of each strip at the center of span, for increments of load up to failure, were measured with a micrometer dial reading to 0.001 inch. The deflection data were used to compute the tangent modulus of elasticity at the origin and the secant modulus of elasticity at failure.

The most convenient location in the broken pipe from which to obtain material for the strips was near the crack which had resulted in the failure of the pipe in the loading test. Since the metal in this area had been subjected to high stress it was necessary to make a preliminary investigation to determine if the physical characteristics of the metal had been materially altered by the stress to which it had been subjected. In this connection it should be noted that the direction of bending in the tests of the pipe was at right angles to that in the bending tests on the strips.

For the preliminary investigation, 3 strips were cut from each of 5 locations in the half circumference of the shell of one of the 48-inch pipes with plain ends of manufacturer A (specimen SP-48-1). The strips were taken from the top (about 2 inches from the crack) and bottom of the shell, from a location on the horizontal axis through the center line and from points midway between this and the top and bottom. Thus there were specimens from two areas of maximum positive bending moment, one area of maximum negative moment, and two areas where the bending moment was very small.

The moduli of elasticity and of rupture calculated from the results of flexure tests on these strips are given in table 10. The results indicated that three strips, one from each of three locations, were defective and the values for these were not included in the calculations of average values. The individual values, exclusive of those of the defective strips, are quite con-

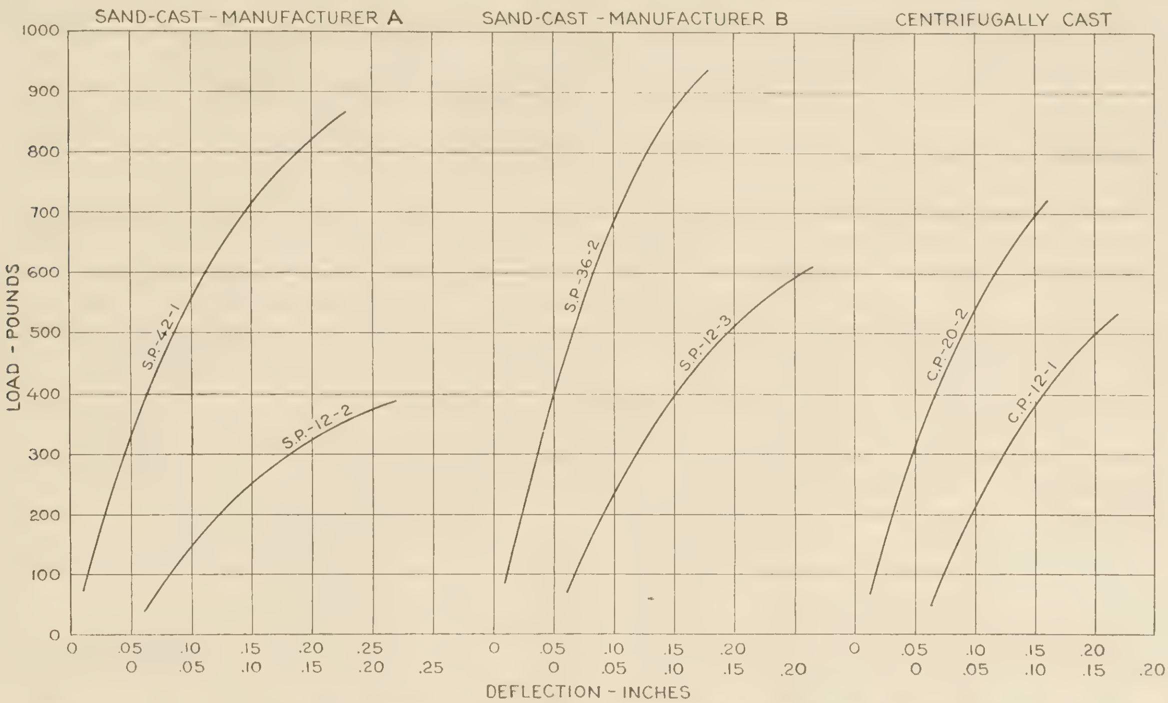

FIGURE 12.—TYPICAL LOAD-DEFLECTION CURVES OF STRIPS FROM SMOOTH CAST-IRON PIPE WITH PLAIN ENDS.

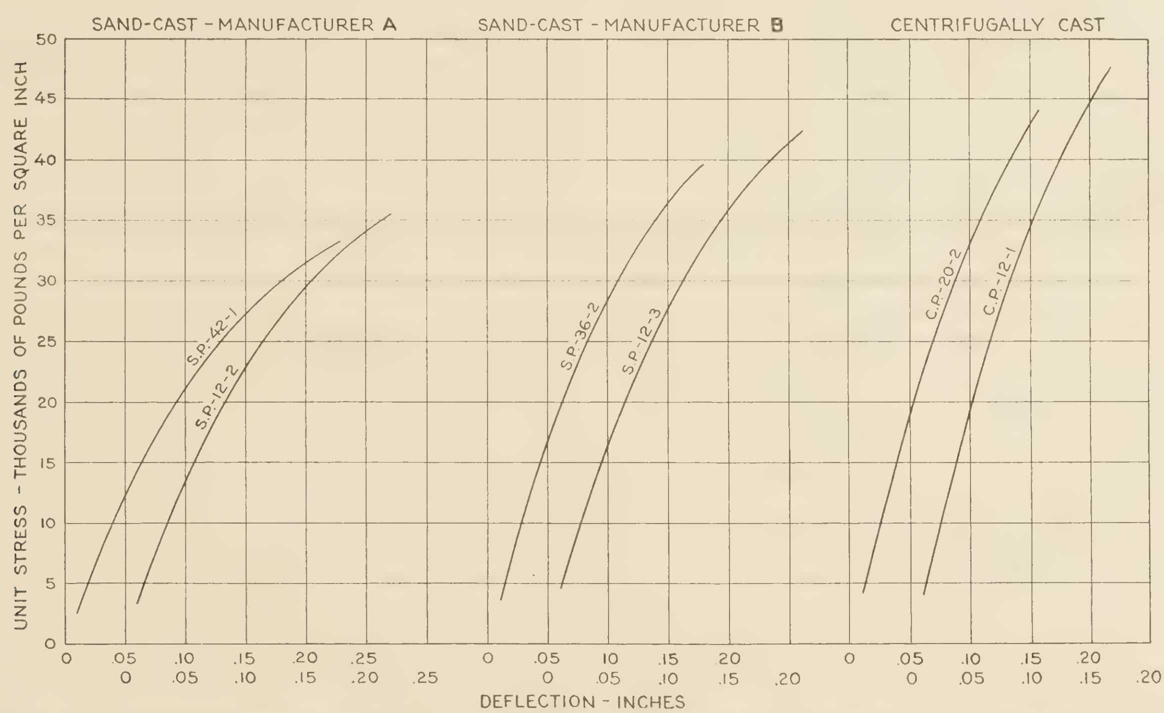

FIGURE 13.—TYPICAL STRESS-DEFLECTION CURVES OF STRIPS FROM SMOOTH CAST-IRON PIPE WITH PLAIN ENDS.

sistent and the average values show no significant differences between strips taken from areas of high stress and those taken from areas of low stress. Table 10 shows that none of the defective strips were taken near the crack nor at the bottom of the pipe, the two positions of greatest bending moment. Therefore, it was concluded that the test strips from the other pipe might safely be taken from the vicinity of the crack which had developed under the loading test, and this was done.

RESULTS OF STRIP TESTS DISCUSSED

The results obtained in the strip tests are given in tables 11, 12, and 13, and typical load-deflection and stress-deflection curves are shown in figures 12 and 13.

In general, 3 strips from each pipe specimen were tested but in a number of cases, where flaws were observed, additional specimens were machined and tested. In most cases flaws in the metal could not be detected by visual examination before the strips had been broken and in numerous cases the flaws

TABLE 10.—*Tests on strips from five positions in one 48-inch pipe*

[Modulus of rupture of pipe—31,800 pounds per square inch]

Location of strips in pipe	Modulus of elasticity		Modulus of rupture
	Origin	Failure	
	Million lb. per sq. in.	*Million lb. per sq. in.*	*Lb. per sq. in.*
Top	11.50	4.60	33,100
	10.35	4.65	32,500
	10.85	4.79	33,300
Average	10.90	4.68	33,000
45° from top	12.38	5.02	32,300
	11.85	4.89	31,900
	10.93	6.17	[1] 19,600
Average	12.12	4.96	32,100
90° from top	10.67	4.75	33,600
	8.64	5.97	[1] 22,400
	8.51	4.57	31,500
Average	9.59	4.66	32,600
45° from bottom	11.60	6.07	[1] 26,200
	11.20	4.77	31,900
	11.22	4.84	32,900
Average	11.21	4.80	32,400
Bottom	12.50	4.80	32,800
	12.46	4.93	33,200
	12.61	4.88	34,000
Average	12.52	4.87	33,300
Grand average	11.34	4.79	32,800

[1] Values for this strip excluded from averages.

which were observed had no apparent influence on the strength of the metal. For instance, 2 of the 3 strips from pipe SP-20-2 (table 11) had flaws and yet the modulus of rupture of both of these strips is higher than that of the strip in which no flaw was detected.

The test results for all strips, whether defective or not, are included in the tables and all results have been used in computing average values except in the case of the average values of the ratio of modulus of rupture of strips to modulus of rupture of pipe (column 11, table 11, columns 11 and 20, table 12, and column 11, table 13). The following explanation is given for this procedure which is at variance with that usually followed in experimental work of this nature.

The strip test has been proposed as a specification requirement to replace, at least to some extent, the more cumbersome and more expensive 3-edge bearing test on full-size specimens of pipe. If this is to be done, the strength developed by the strips should be indicative of the modulus of rupture of the pipe as determined in the 3-edge test. A study of the data shows that flaws in the strips in some cases resulted in a material reduction of the modulus of rupture and in other cases did not. The data also show that strips with flaws and of low strength were sometimes obtained from pipe of more than average strength and, conversely, that strips of more than average strength were sometimes obtained from pipe of relatively low strength. It appears that, in routine testing to determine compliance with specifications, low strength due to flaws in strips would not necessarily be indicative of low-strength pipe. It is felt that, in the study of the suitability of the strip test for the proposed purpose, the test values of all specimens are of equal importance in arriving at conclusions.

As has been stated, the surfaces of the strips were ground to remove the coating of pitch and any adhering sand before testing. In the case of the sand-cast pipe of manufacturer A and the centrifugally cast pipe this did not result in appreciable reduction in the breadth of the specimen. However, the surfaces of the sand-cast pipe of manufacturer B contained a considerable amount of embedded sand and the removal of this by grinding reduced the breadth of the specimens by varying amounts, frequently as much as several hundredths

TABLE 11.—*Results of bending tests on strips from smooth sand-cast pipe with plain ends, manufacturer A*

Identification no.	Modulus of elasticity of strips				Modulus of rupture of strips	Average	Deviation from grand average	Modulus of rupture of pipe	Ratio of modulus of rupture of strips to modulus of rupture of pipe		Remarks
	At origin	Average	At failure	Average							
1	2	3	4	5	6	7	8	9	10	11	
	Million lb. per sq. in.	*Million lb. per sq. in.*	*Million lb. per sq. in.*	*Million lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Per-cent*	*Lb. per sq. in.*		*Aver-age*	
SP-12-1	13.37	13.44	9.13	8.86	35,100	36,600	2.8	42,300	0.83	0.87	
	13.94		9.22		36,500		1.1		.86		
	13.01		8.24		38,300		6.1		.91		
2	11.06	11.83	8.44	7.29	26,400	32,200	26.9	40,300	*.66	[1] .87	Flaw at break.
	[2] 11.79		6.71		36,400		.8		.90		
	12.63		6.71		33,800		6.4		.84		
3	11.26	11.18	5.66	6.50	35,900	34,600	.6	39,700	.90	[1] .91	
	10.97		7.10		31,500		12.7		*.79		Do.
	11.30		6.75		36,300		.6		.91		
Average	12.15		7.55		34,500			40,800	.85	[1] .88	
SP-16-1	12.76	12.77	6.92	7.27	41,900	39,800	16.1	35,900	1.17	1.11	
	12.98		7.88		37,400		3.6		1.04		
	12.56		7.03		40,000		10.8		1.11		Broke 0.05 inch outside middle third.
2	11.88	12.77	7.15	7.27	38,600	40,200	6.9	39,100	.99	1.03	Broke 0.23 inch outside middle third.
	12.46		7.33		41,600		15.2		1.06		
	13.96		7.33		40,400		11.9		1.03		
3	9.57	10.00	6.20	6.10	35,800	37,700	.8	38,000	.94	.99	
	9.50		5.94		37,600		4.2		.99		
	10.94		6.15		39,800		10.2		1.05		Specimen warped.
Average	11.85		6.88		39,200			37,700	1.04	1.04	

TABLE 11.—*Results of bending tests on strips from smooth sand-cast pipe with plain ends, manufacturer A*—Continued

Identification no.	Modulus of elasticity of strips				Modulus of rupture of strips	Average	Deviation from grand average	Modulus of rupture of pipe	Ratio of modulus of rupture of strips to modulus of rupture of pipe		Remarks
	At origin	Average	At failure	Average							
1	2	3	4	5	6	7	8	9	10	11	
	Million lb. per sq. in.	*Million lb. per sq. in.*	*Million lb. per sq. in.*	*Million lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Per-cent*	*Lb. per sq. in.*		*Average*	
SP-20-1	11.59	11.98	5.67	6.07	40,200	38,800	11.4	43,300	0.93	0.90	
	12.39		6.22		37,200		3.0		.86		Flaw at break.
	11.95		6.31		38,900		7.8		.90		Specimen warped.
2	12.75	13.04	6.21	6.37	40,400	39,200	11.9	43,700	.92	.90	Flaw at break.
	13.11		6.69		36,300		.6		.83		
	13.25		6.22		40,800		13.0		.93		Do.
3	14.11	13.81	6.61	6.64	39,100	37,800	8.3	37,300	1.05	1.01	
	13.36		6.52		37,200		3.0		1.00		
	13.95		6.80		37,100		2.8		.99		
Average	12.94		6.36		38,600			41,400	.93	.93	
SP-24-1	11.95	12.86	8.18	7.74	29,200	34,500	19.1	32,800	*.89	[1] 1.09	Flaw at break. Broke 0.23 inch outside middle third.
	12.37		7.05		35,400		1.9		1.08		Flaw at break.
	12.33		6.95		35,800		.8		1.09		Do.
	13.69		8.27		35,000		3.0		1.07		Do.
	13.17		8.45		34,800		3.6		1.06		Do.
	13.64		7.53		37,000		2.5		1.13		Do.
2	12.77	12.92	8.23	6.99	33,600	37,500	6.9	38,400	*.87	[1] 1.00	Specimen cracked.
	13.00		6.76		37,200		3.0		.97		Flaw at break.
	12.33		6.87		35,900		.6		.94		Do.
	12.92		6.83		37,900		5.0		.99		Do.
	13.81		6.29		43,800		21.3		1.14		
	12.69		6.96		36,700		1.7		.96		
3	10.82	11.48	6.23	6.42	38,300	38,100	6.1	43,400	.88	.88	
	12.50		6.40		38,700		7.2		.89		
	11.13		6.64		37,200		3.0		.86		
Average	12.61		7.18		36,400			38,200	.95	[1].97	
SP-30-1	10.35	11.20	5.17	4.98	38,400	38,600	6.4	39,800	.96	.97	
	11.67		4.96		38,600		6.9		.97		
	11.58		4.82		38,800		7.5		.97		
2	10.59	10.28	4.61	4.57	33,900	34,200	6.1	32,000	1.06	1.07	
	10.00		4.46		34,000		5.8		1.06		
	10.24		4.63		34,600		4.2		1.08		
3	10.89	10.83	5.29	5.08	33,200	34,500	8.0	31,500	1.05	1.10	
	10.56		4.92		34,000		5.8		1.08		
	11.04		5.02		36,400		.8		1.16		
Average	10.77		4.88		35,800			34,400	1.04	1.04	
SP-36-1	11.33	11.58	6.00	6.06	37,700	38,100	4.4	35,600	1.06	1.07	
	11.56		6.20		38,800		7.5		1.09		
	11.84		5.98		37,900		5.0		1.06		
3	10.16	10.77	6.87	5.78	21,000	29,100	41.8	33,700	*.62	[1].98	Specimen cracked.
	11.07		5.30		32,400		10.2		.96		
	11.08		5.17		33,900		6.1		1.01		
Average	11.17		5.92		33,600			34,600	.97	[1] 1.04	
SP-42-1	[2] 11.53	12.07	6.21	6.10	33,900	37,600	6.1	36,500	.93	1.03	
	12.19		6.13		38,700		7.2		1.06		
	12.49		5.97		40,300		11.6		1.10		
2	10.30	10.73	4.54	4.55	33,400	33,000	7.5	35,700	.94	.92	
	10.84		4.65		33,100		8.3		.93		
	11.06		4.45		32,500		10.0		.91		
3	12.80	12.79	5.41	5.32	37,100	37,100	2.8	40,800	.91	.91	
	12.80		5.32		37,100		2.8		.91		
	12.78		5.22		37,100		2.8		.91		
Average	11.87		5.32		35,900			37,700	.95	.95	
SP-48-1	11.50	10.90	4.60	4.68	33,100	33,000	8.3	31,800	1.04	1.04	
	10.35		4.65		32,500		10.0		1.02		
	10.85		4.79		33,300		7.8		1.05		
2	10.02	10.12	5.08	5.07	33,200	33,000	8.0	36,100	.92	.91	
	10.35		5.06		33,300		7.8		.92		
	10.00		5.08		32,500		10.0		.90		
3	11.80	11.69	5.69	5.63	35,900	36,200	.6	32,700	1.10	1.11	
	10.89		5.69		36,100		.0		1.10		
	12.38		5.51		36,700		1.7		1.12		
Average	10.90		5.13		34,100			33,500	1.02	1.02	
Grand average	11.87		6.24		36,100		7.0	37,400	.97	[1].98	

[1] Values marked with asterisk (*) omitted from this average.
[2] Deflection data for this strip shown in figs. 12 and 13.

TABLE 12.—*Results of bending tests on strips from smooth sand-cast pipe, plain ends, manufacturer B*

Identification no.	Unground strips									
	Modulus of elasticity of strips				Modulus of rupture of strips	Average	Deviation from grand average	Modulus of rupture of pipe	Ratio of modulus of rupture of strips to modulus of rupture of pipe	
	At origin	Average	At failure	Average						
1	2	3	4	5	6	7	8	9	10	11
	Million lb. per sq. in.	*Million lb. per sq. in.*	*Million lb. per sq. in.*	*Million lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Percent*	*Lb. per sq. in.*		*Average*
SP-12-1	14.42	15.39	7.82	7.66	46,200	48,300	20.9	31,100	1.48	1.55
	15.93		7.57		49,200		28.8		1.58	
	15.82		7.60		49,600		29.8		1.59	
2	14.29	14.07	7.98	7.74	45,000	44,500	17.8	32,100	1.40	1.39
	14.68		7.41		45,400		18.8		1.41	
	13.24		7.84		43,000		12.6		1.34	
3	13.87	12.99	7.88	8.41	41,800	38,200	9.4	37,300	1.12	[1] 1.08
	13.65		8.08		40,700		6.5		1.09	
	13.08		8.65		38,100		.3		1.02	
	12.54		7.83		41,900		9.7		1.12	
	12.73		9.27		33,600		12.0		*.90	
	12.67		7.60		38,600		1.0		1.03	
	12.41		9.54		32,500		14.9		*.87	
Average	13.79		8.08		42,000			33,500	1.25	[1] 1.30
SP-18-1	15.30	15.40	8.92	9.44	46,900	45,500	22.8	27,300	1.72	[1] 1.75
	15.32		8.87		48,700		27.5		1.78	
	15.58		10.54		40,800		6.8		* 1.49	
2	13.38	13.72	8.71	8.77	34,200	38,300	10.5	36,900	.93	1.04
	14.25		8.98		41,100		7.6		1.11	
	13.53		8.62		39,700		3.9		1.08	
3	13.82	13.91	9.33	8.84	40,600	39,900	6.3	40,500	1.00	.99
	14.38		8.78		39,900		4.5		.99	
	13.52		8.42		39,100		2.4		.97	
Average	14.34		9.02		41,200			34,900	1.18	[1] 1.18
SP-24-1	14.90	14.62	8.43	8.35	41,500	39,700	8.6	31,500	1.32	1.26
	14.05		8.08		38,600		1.0		1.23	
	14.92		8.54		39,100		2.4		1.24	
2	14.18	14.37	7.40	7.76	43,600	42,400	14.1	37,200	1.17	1.14
	14.26		7.73		41,700		9.2		1.12	
	14.67		8.15		42,000		9.9		1.13	
3	12.92	13.28	8.64	9.36	35,300	31,100	7.6	37,500	.94	[1] .90
	13.18		8.47		32,700		14.4		.87	
	13.76		9.75		27,300		28.5		*.73	
	13.38		9.52		32,700		14.4		.87	
	13.09		10.52		24,000		37.2		*.64	
	13.32		9.27		34,500		9.7		.92	
Average	13.89		8.71		36,100			35,400	1.02	[1] 1.08
SP-30-1	12.88	14.02	8.52	9.08	34,300	32,600	10.2	33,800	1.01	[1] 1.02
	14.68		8.64		34,500		9.7		1.02	
	14.49		10.09		29,000		24.1		*.86	
2	12.96	12.96	8.12	7.95	32,700	35,100	14.4	35,000	.93	1.00
	12.10		7.40		36,000		5.8		1.03	
	13.82		8.33		36,500		4.5		1.04	
3	13.96	13.45	7.50	8.23	37,200	33,400	2.6	32,100	1.16	1.09
	12.21		8.57		30,100		21.2		*.94	
	14.19		8.62		32,800		14.1		1.02	
Average	13.48		8.42		33,700			33,600	1.00	[1] 1.04
SP-36-1	13.20	13.37	6.80	6.89	35,700	34,700	6.5	34,500	1.03	1.01
	13.35		7.20		33,900		11.3		.98	
	13.55		6.66		34,600		9.4		1.00	
2	13.85	14.05	8.59	7.98	36,900	38,700	3.4	33,800	1.09	1.14
	13.76		7.34		40,100		5.0		1.19	
	14.53		8.00		39,000		2.1		1.15	
Average	13.71		7.43		36,700			34,200	1.07	1.07
Grand average	13.85		8.39		38,200		11.8	34,300	1.11	[1] 1.15

[1] Values marked with asterisk (*) are omitted from this average.

of an inch. Moduli of rupture computed on the basis of the dimensions of the ground strips are undoubtedly more indicative of the strength of the metal itself than are similar values computed on the basis of the dimensions of the strips before grinding. However, moduli computed on the latter basis are more directly comparable to the moduli reported for the pipe specimens, since these were calculated on the basis of the gross thickness of shell, including embedded sand. Therefore, in table 12 which shows the results obtained on strips from the pipe of manufacturer B, values of moduli of elasticity and rupture are reported for both unground and ground strips. The tests were made on the strips after grinding, and no tests were actually made on unground strips.

The moduli of elasticity and rupture reported for unground strips were obtained by using the loads and deflections of the ground strips and the dimensions of the strips in their original condition including the thickness of embedded sand. Since the grinding operation

TABLE 12.—*Results of bending tests on strips from smooth sand-cast pipe, plain ends, manufacturer B*—Continued

Identification no.	Ground strips									Remarks
	Modulus of elasticity of strips				Modulus of rupture of strips	Average	Deviation from grand average	Ratio of modulus of rupture of strips to modulus of rupture of pipe		
	At origin	Average	At failure	Average						
1	12	13	14	15	16	17	18	19	20	
	Million lb. per sq. in.	*Million lb. per sq. in.*	*Million lb. per sq. in.*	*Million lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Percent*		*Average*	
SP-12-1	14.70	15.68	7.97	7.81	47,100	49,300	16.0	1.51	1.59	
	16.23		7.71		50,100		23.4	1.61		
	16.11		7.74		50,600		24.6	1.63		
2	14.57	14.35	8.14	7.90	45,900	45,400	13.1	1.43	1.41	
	14.98		7.56		46,400		14.3	1.45		
	13.51		8.00		43,900		8.1	1.37		
3	14.37	13.51	8.16	8.74	43,300	39,700	6.7	1.16	[1] 1.12	Flaw at break.
	[2] 14.14		8.37		42,200		3.9	1.13		Do.
	13.54		8.95		39,400		3.0	1.06		Do.
	13.08		8.17		43,700		7.6	1.17		Do.
	13.29		9.68		35,100		13.5	*.94		Do.
	13.20		7.92		40,200		1.0	1.08		Flaw at break. Broke 0.4 inch outside middle third.
	12.94		9.95		33,900		16.5	*.91		Flaw at break.
Average	14.20		8.33		43,200			1.29	[1] 1.34	
SP-18-1	15.98	16.08	9.31	9.86	49,000	47,500	20.7	1.79	[1] 1.83	
	15.99		9.26		50,900		25.4	1.86		
	16.27		11.00		42,600		4.9	* 1.56		Do.
2	14.09	14.44	9.17	9.23	35,900	40,300	11.6	.97	1.09	
	15.00		9.45		43,200		6.4	1.17		Broke 0.14 inch outside middle third.
	14.24		9.07		41,800		3.0	1.13		
3	15.50	15.58	10.46	9.91	45,600	44,700	12.3	1.13	1.10	
	16.15		9.87		44,700		10.1	1.10		Broke 0.42 inch outside middle third.
	15.08		9.39		43,700		7.6	1.08		
Average	15.37		9.66		44,200			1.27	[1] 1.27	
SP-24-1	15.96	15.67	9.03	8.95	44,500	42,600	9.6	1.41	1.35	
	15.06		8.66		41,300		1.7	1.31		Broke 0.23 inch outside middle third.
	15.98		9.15		41,900		3.2	1.33		
2	15.11	15.31	7.89	8.27	46,500	45,200	14.5	1.25	1.22	Specimen warped.
	15.19		8.23		44,400		9.4	1.19		
	15.64		8.69		44,700		10.1	1.20		
3	13.80	14.17	9.23	10.00	37,700	33,200	7.1	1.01	[1] .96	Flaw at break.
	14.07		9.04		35,000		13.8	.93		Do.
	14.69		10.41		29,100		28.3	*.78		Do.
	14.29		10.17		34,900		14.0	.93		Flaw at break. Broke 0.15 inch outside middle third.
	13.97		11.23		25,600		36.9	*.68		
	14.22		9.90		36,800		9.4	.98		Flaw at break. Broke 0.05 inch outside middle third.
Average	14.83		9.30		38,500			1.09	[1] 1.15	
SP-30-1	13.26	14.43	8.77	9.35	35,400	33,600	12.8	1.05	[1] 1.05	
	15.12		8.90		35,500		12.6	1.05		
	14.92		10.39		29,900		26.4	*.88		Flaw at break.
2	14.40	14.39	9.02	8.83	36,400	39,000	10.3	1.04	1.11	Do.
	13.45		8.22		40,000		1.5	1.14		
	15.33		9.24		40,500		.2	1.16		
3	15.48	14.92	8.32	9.13	41,200	37,000	1.5	1.28	[1] 1.21	
	13.55		9.51		33,400		17.7	* 1.04		Do.
	15.74		9.56		36,400		10.3	1.13		
Average	14.58		9.10		36,500			1.09	[1] 1.13	
SP-36-1	14.88	15.08	7.67	7.77	40,200	39,100	1.0	1.17	1.13	
	15.06		8.12		38,200		5.9	1.11		
	15.30		7.51		39,000		3.9	1.13		Broke 0.13 inch outside middle third.
2	[2] 14.77	14.97	9.16	8.50	39,400	41,300	3.0	1.17	1.22	
	14.66		7.82		42,800		5.4	1.27		
	15.49		8.52		41,600		2.5	1.23		
Average	15.03		8.13		40,200			1.18	1.18	
Grand average	14.74		8.93		40,600		10.8	1.18	[1] 1.22	

[2] Deflection data for this strip shown in Figures 12 and 13.

unavoidably removed small amounts of surface metal, the strips in their original or unground condition probably would have supported somewhat greater loads than they did in the tests which were made. Therefore, the moduli reported for the unground strips in the first part of table 12 are probably somewhat lower than the true values but it is not believed that the error involved is large enough to be of any importance.

All average values given in tables 11, 12, and 13 are weighted averages and are based on all the test results, irrespective of defects in individual specimens, with the exception of the average values given in column 11 of table 11, columns 11 and 20 of table 12 and column 11 of table 13. In these columns are given the averages of the ratios of modulus of rupture of strips to modulus of rupture of pipe, and the moduli of strips manifestly

TABLE 13.—*Results of bending tests on strips from smooth centrifugally cast pipe with plain ends*

Identification no.	Modulus of elasticity of strips: At origin	Modulus of elasticity of strips: Average	Modulus of elasticity of strips: At failure	Modulus of elasticity of strips: Average	Modulus of rupture of strips	Average	Deviation from grand average	Modulus of rupture of pipe	Ratio of modulus of rupture of strips to modulus of rupture of pipe [1]		Remarks
1	2	3	4	5	6	7	8	9	10	11	
	Million lb. per sq. in.	*Million lb. per sq. in.*	*Million lb. per sq. in.*	*Million lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Percent*	*Lb. per sq. in.*		*Average*	
CP-12-1	16.22	16.32	13.15	12.38	52,000	52,400	13.5	50,000	1.04	1.05	
	[2] 16.17		11.71		51,100		11.6		1.02		
	16.57		12.27		54,000		17.9		1.08		
2	16.99	17.47	14.03	13.25	41,400	44,100	9.6	54,700	.76	.81	
	17.49		13.54		45,400		.9		.83		
	17.94		12.18		45,500		.7		.83		
3	14.40	14.51	11.81	12.40	52,200	44,500	14.0	53,600	.97	[1] .93	
	14.16		12.55		47,100		2.8		.88		Specimen warped.
	14.98		12.84		34,100		25.6		*.64		Specimen warped. Broke 0.9 inch outside middle third.
Average	16.10		12.68		47,000			52,800	.89	[1] .92	
CP-16-1	15.09	15.39	12.07	12.63	44,100	42,300	3.7	55,700	.79	.76	
	14.43		11.73		41,800		8.7		.75		Broke 0.07 inch outside middle third.
	16.66		14.10		40,900		10.7		.73		
2	16.75	16.87	11.12	10.85	51,600	50,500	12.7	59,700	.86	.85	
	16.70		11.27		48,400		5.7		.81		
	17.16		10.17		51,500		12.4		.86		
3	16.35	16.77	11.48	11.43	45,400	45,700	.9	51,500	.88	.89	
	16.34		11.21		46,200		.9		.90		
	17.62		11.61		45,400		.9		.88		
Average	16.34		11.64		46,100			55,600	.83	.83	
CP-20-1	16.87	16.54	9.49	10.15	53,800	45,200	17.5	44,700	1.20	[1] 1.18	
	16.09		10.56		30,400		33.6		*.68		Specimen cracked.
	16.66		10.41		51,300		12.0		1.15		
2	15.58	15.70	11.74	11.47	45,500	46,200	.7	49,000	.93	.94	
	15.51		10.84		48,100		5.0		.98		
	[2] 16.00		11.83		45,100		1.5		.92		
3	15.94	16.08	11.45	11.86	43,200	41,900	5.7	52,100	.83	.80	
	15.70		11.83		41,800		8.7		.80		
	16.61		12.31		40,600		11.4		.78		
Average	16.11		11.16		44,400			48,600	.91	[1] .95	
Grand average	16.18		11.83		45,800		9.2	52,300	.88	[1] .90	

[1] Values marked with asterisk (*) are omitted from the average.

[2] Deflection data for this strip shown in figures 12 and 13.

defective have been omitted in order to show the small effect on the grand averages of these columns as compared with the grand averages of the columns immediately preceding which are based on all test results. The omission of test results in the computation of these averages was based entirely on personal judgment. If the modulus of a strip was materially lower than the average of the other strips from that pipe, it was discarded; otherwise it was retained.

For each strip, two values of modulus of elasticity are reported; the secant modulus at failure and the tangent modulus at the origin. Of the two, the secant modulus is more suitable for use as a specification requirement on account of the greater ease and accuracy of its determination. The modulus at the origin is of some interest in showing the maximum value of modulus of elasticity which may be obtained in this test.

The average modulus of rupture of strips taken from the centrifugally-cast pipe is relatively high as was the case in the tests on full-size specimens. It may also be noted that in the tests of pipe the sand-cast pipe of manufacturer A developed a higher average modulus than the sand cast pipe of manufacturer B, while in the strip tests the reverse is true. The average modulus of 45,800 pounds per square inch for the strips of centrifugally cast metal may be compared with an average modulus of 38,200 pounds per square inch for the unground strips of sand-cast metal of manufacturer B and 36,100 pounds per square inch for the strips from the sand-cast metal of manufacturer A. The ground strips from the sand-cast pipe of manufacturer B developed an average modulus of rupture of 40,600 pounds per square inch. The inclusion, in the computations, of the thickness of the embedded surface sand had the effect of reducing the average modulus about 6 percent to 38,200 pounds per square inch.

The consistency of the values of modulus of rupture developed by individual strips is indicated by the average deviations of 7.0 percent, 9.2 percent, and 11.8 percent, respectively, for the sand-cast metal of manufacturer A, the centrifugally cast metal and the unground strips of the sand-cast metal of manufacturer B. The relatively low average deviation of the moduli of rupture developed in the tests of centrifugally cast pipe may be thought to be indicative of a more uniform product, but this indication is not corroborated by the above results from tests on the metals themselves. The moduli of rupture of the ground strips (table 12) are somewhat more consistent than those of the unground strips. This is to be expected since the low-strength material ground from the surface of the strips was not of uniform thickness.

STRIP TESTS NOT A SATISFACTORY INDICATION OF PIPE STRENGTH

As in the case of the pipe specimens, the moduli of rupture of individual strips vary through a rather wide range. For the sand-cast strips of manufacturer A the modulus of rupture varies from a minimum of 21,000 pounds per square inch to a maximum of 43,800 pounds per square inch with a maximum deviation from the average of 41.8 percent. If the defective specimens are excluded, the range is from 32,400 to 43,800 pounds per square inch. For the unground sand-cast strips of manufacturer B, the variation is from 24,000 to 49,600 with a maximum deviation of 37.2 percent. Exclusive of defective specimens the range is from 32,700 to 49,600 pounds per square inch. Strips from the centrifugally cast pipe give a range in values of moduli of rupture from 30,400 to 54,000 pounds per square inch with a maximum deviation of 33.6 percent. Exclusive of specimens manifestly defective the range is from 40,600 to 54,000 pounds per square inch.

In the strip tests there is the same general, though far from consistent trend toward somewhat lower values of moduli of rupture with increasing thickness of metal as was the case in the pipe tests. However, the relationship is too vague to be of practical significance.

Both the tangent modulus of elasticity at origin and the secant modulus at failure, show the centrifugally cast metal to be considerably stiffer than the sand-cast metal. Average values for the tangent modulus at origin are 11,870,000 pounds per square inch, 13,850,000 pounds per square inch and 16,180,000 pounds per square inch, respectively, for the sand-cast metals of manufacturer A, manufacturer B, and the centrifugally cast metal. Corresponding values for the secant modulus at failure are 6,240,000, 8,390,000, and 11,830,000 pounds per square inch. Here, also, there is some indication of a general trend toward decreasing values with increasing thickness of metal, which appears to be somewhat more pronounced for the modulus at failure than for the modulus at origin, and more pronounced in the metal of manufacturer A and the centrifugally cast metal than in the metal of manufacturer B.

Possibly the most important data resulting from the strip tests are the calculated ratios of the modulus of rupture of each strip to the modulus of rupture of the pipe from which it was taken, and the average values of these ratios.

Including all strips, the values of the modulus ratio for the sand-cast pipe of manufacturer A range from 0.62 to 1.17, with an average of 0.97. The exclusion of badly defective strips changes the range to 0.83 to 1.17 and the average to 0.98. The ratios for the centrifugally cast pipe range from 0.64 to 1.20, with an average of 0.88 for all strips and, exclusive of defective specimens, an average of 0.90 with a range of 0.73 to 1.20.

The modulus ratios for the unground strips from the sand-cast pipe of manufacturer B range from 0.64 to 1.78, with an average of 1.11, and the range for the ground strips is from 0.68 to 1.86, with an average of 1.18. The exclusion of defective strips changes the ranges of individual values to 0.87 to 1.78 and 0.93 to 1.86, respectively, with average values of 1.15 and 1.22.

It will be observed that there is a considerable difference between the average values of the modulus ratios for the three groups of pipe. It will also be observed that the exclusion of the ratios for defective strips does not alter the average values materially and that there is the same general relationship between them irrespective of whether the defective strips are included or discarded.

It is, perhaps, to be expected that the average modulus ratio for the centrifugally cast pipe should differ from those for the sand-cast pipe, since the physical characteristics of the metals themselves differ considerably. However, if the strength of strips is to be accepted as a measure of the strength of the pipe from which they are taken, a reasonably close agreement should exist between the modulus ratios for two sets of pipe cast in a similar manner and of metal of similar characteristics. This agreement does not exist for the sand-cast pipe, the average modulus ratios for all specimens being 0.97 for manufacturer A and 1.11 for the unground strips of manufacturer B.

It has been pointed out that (1) obviously defective strips may be obtained from pipe of more than average strength; (2) that strips of relatively high strength may be obtained from pipe of less than average strength; (3) that there is a wide range in the individual values of the modulus ratios; and (4) that there is lack of agreement between the average modulus ratios for two groups of pipe of the same general character. These facts lead to the conclusion that the results of tests on small strips cut from pipe are not acceptable indices of the strength which the pipe may be expected to develop in the 3-edge bearing test.

USE OF TEST RESULTS IN PREPARATION OF SPECIFICATIONS

During the progress of the investigation which has been described, the results as they were obtained were made available from time to time to a committee of the American Society for Testing Materials which was engaged in the preparation of tentative specifications for cast-iron culvert pipe. These specifications, A.S.T.M. Designation: A142-32T, which have now been published as tentative standards of the society, are believed to be the first specifications for cast-iron culvert pipe in which the required shell thicknesses have been established on a rational basis.

These tentative specifications recognize three classes of pipe known as standard, heavy, and extra-heavy pipe for which the required minimum strengths in the 3-edge bearing test are, respectively, 2,000 D, 3,000 D, and 4,000 D pounds per foot of laying length.

The shell thicknesses for smooth pipe were calculated on the basis of equation 9 for a modulus of rupture of 30,000 pounds per square inch and the thicknesses so determined were arbitrarily increased by 10 percent. Table 14 gives the specified shell thicknesses and their derivation.

TABLE 14.—*Shell thickness of smooth cast-iron culvert pipe as required by A.S.T.M. tentative standard specification, A142-32T*

Nominal diameter of pipe (inches)	Standard pipe (2,000 D)			Heavy pipe (3,000 D)			Extra-heavy pipe (4,000 D)		
	Theoretical thickness [1]	Theoretical thickness plus 10 percent	Specified thickness	Theoretical thickness [1]	Theoretical thickness plus 10 percent	Specified thickness	Theoretical thickness [1]	Theoretical thickness plus 10 percent	Specified thickness
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
12	0.255	0.281	0.37	0.313	0.344	0.37	0.362	0.398	0.40
14	.298	.328	.37	.365	.402	.40	.423	.465	.46
16	.340	.374	.40	.417	.459	.46	.483	.531	.53
18	.383	.421	.42	.470	.517	.52	.543	.597	.60
20	.425	.468	.47	.522	.574	.57	.604	.664	.66
24	.510	.561	.56	.626	.689	.69	.724	.796	.80
30	.638	.702	.70	.783	.861	.86	.905	.996	1.00
36	.765	.842	.84	.939	1.033	1.03	1.086	1.195	1.20
42	.893	.982	.98	1.096	1.206	1.20	1.268	1.395	1.40
48	1.020	1.122	1.12	1.252	1.378	1.38	1.449	1.594	1.60

[1] Theoretical thicknesses calculated for modulus of rupture of 30,000 pounds per square inch.

It will be noted that the specified thicknesses of the 12-, 14-, and 16-inch standard pipe and of the 12-inch heavy pipe are somewhat greater than the theoretical thicknesses increased by 10 percent. In these cases arbitrary increases were made in order that the required thickness of metal be not less than three eighths of an inch.

If the moduli of rupture obtained in the tests which have been reported may be considered generally representative of the values which would be obtained with any commercially available cast-iron culvert pipe, then the modulus of 30,000 pounds per square inch, which is the basis of design in the tentative specifications, may be considered somewhat conservative since it is somewhat lower than the average values which were obtained with sand-cast pipe. However, the modulus of one pipe tested was less than 30,000 pounds per square inch and the moduli of a considerable proportion were between 30,000 and 35,000 pounds per square inch. In any case, any conservatism in the matter of unit stress is balanced to some extent by the provision of the specification which permits a maximum underrun in thickness of 15 percent.

CONCLUSIONS

The following conclusions, based on the results obtained in this investigation, are presented:

1. In the 3-edge bearing test for pipe with bell ends it is preferable to locate the point or center of load application, on the upper bearing block, at the center of pipe rather than at the center of length of bearing.
2. The design of cast-iron pipe to withstand the 3-edge bearing test may more safely be based on the results of tests on specimens with plain ends than on the results obtained on specimens with bell ends, due to the variable and uncertain influence of the bell ends on the supporting strength.
3. The pipe included in this investigation which were centrifugally cast in metal contact molds were of considerably higher strength than the sand-cast pipe.
4. Spiral corrugated pipe and ribbed pipe, similar in all respects to those included in this investigation, may be expected to develop a strength in the 3-edge bearing test of at least 2,000 D pounds per linear foot of laying length.
5. The magnitude of the vertical deflections of pipe under a given load in the 3-edge bearing test is influenced by the type of design, the quality of the metal, and the details of design. For the smooth pipe included in this study the magnitude of these deflections was influenced more by variations in the ratio of shell thickness to diameter than by variations in the modulus of elasticity of the metal.
6. The modulus of rupture of small strips cut from a specimen of pipe is not a good index of the modulus of rupture which the pipe will develop in the 3-edge bearing test.

RECOMMENDATIONS

In addition to the above conclusions, it is desired to offer the following recommendations with respect to the design of smooth cast-iron pipe:

1. That the required minimum shell thickness be determined on a rational basis such as is provided by the theoretical equation (9) which has been presented.
2. That the selection of the modulus of rupture to be used in design be made on the basis of the modulus which may be expected in pipe manufactured to meet the design requirements.
3. That, as a safeguard against unavoidable inaccuracies in manufacture, the required nominal shell thickness be made greater than the theoretical thickness as determined by equation (9), by an arbitrary allowance of not less than 10 percent.

CURRENT STATUS OF U.S. PUBLIC WORKS ROAD CONSTRUCTION
AS PROVIDED IN TITLE II, SECTION 204 OF THE NATIONAL INDUSTRIAL RECOVERY ACT

CLASS I—PROJECTS ON THE FEDERAL-AID HIGHWAY SYSTEM
OUTSIDE OF MUNICIPALITIES

AS OF OCTOBER 31,1933

STATE	PUBLIC WORKS FUNDS ASSIGNED FOR CLASS I PROJECTS ON THE FEDERAL AID HIGHWAY SYSTEM	COMPLETED				UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION		BALANCE OF PUBLIC WORKS FUNDS AVAILABLE FOR NEW CLASS I PROJECTS
		Total cost	Public works funds	Regular Federal aid	Mileage	Estimated total cost	Public works funds allotted	Regular Federal aid allotted	Percentage completed	Mileage	Public works funds allotted	Mileage	
	$	$	$	$		$	$	$			$		$
Alabama	4,185,067					1,019,052.26	560,478.75	458,573.51	3.9	38.1	1,475,770.69	154.7	2,148,317.56
Arizona	3,804,731					1,736,625.07	1,734,470.83		7.8	109.6	787,782.12	59.9	1,282,478.05
Arkansas	3,374,167					521,166.78	268,090.09	253,076.69	1.1	3.5	642,812.51	47.0	2,463,264.40
California	7,803,677					4,695,867.16	4,020,372.77		2.2	136.0	1,596,955.68	77.1	2,186,348.55
Colorado	3,437,265					1,019,726.64	1,019,726.64		29.9	54.1	586,461.09	23.1	1,831,077.27
Connecticut	1,404,213					202,625.72	202,625.72		1.5	2.9	60,380.55	.1	1,141,206.73
Delaware	909,544					399,126.30	399,126.30		35.3	19.7	346,978.00	7.5	163,439.70
Florida	2,615,917					1,381,054.43	759,579.92	621,474.51	11.6	50.8	737,828.54	32.9	1,118,508.54
Georgia	5,045,592										582,663.17	23.0	4,462,928.83
Idaho	2,243,125					1,491,706.95	1,488,098.73		18.0	116.5	105,229.71	13.7	649,796.56
Illinois	4,431,348										229,859.90	5.9	4,201,488.10
Indiana	4,717,786					1,174,800.00	1,174,800.00		6.6	46.4	1,219,269.59	34.9	2,323,716.41
Iowa	5,027,830					3,755,606.76	3,533,500.00		29.8	160.2	1,315,400.00	78.5	178,930.00
Kansas	5,044,802					371,785.29	371,785.29		6.2	48.7	2,498,858.55	269.5	2,174,158.16
Kentucky	3,608,332					1,121,901.26	1,121,901.26		.4	82.9	961,119.80	73.4	1,525,310.94
Louisiana	2,914,295					488,288.02	488,288.02		16.8	18.8	1,213,617.51	24.5	1,212,389.47
Maine	1,684,959					802,228.54	802,228.54		27.5	27.8	257,546.33	4.6	625,184.13
Maryland	1,782,263					156,305.93	146,657.18		7.5	4.8	674,613.95	10.0	960,991.87
Massachusetts	1,932,950					380,636.86	195,937.51	179,984.24	43.9	13.1	418,450.25	17.7	1,318,562.24
Michigan	5,094,491					1,069,450.00	1,069,450.00		34.6	69.5	521,700.00	42.3	3,503,341.00
Minnesota	5,115,153					2,069,289.35	2,069,289.33		37.7	359.3	168,063.88	35.4	2,877,799.79
Mississippi	3,489,337					368,235.79	219,800.63	148,435.16	4.1	18.5	217,817.13	25.0	3,051,719.24
Missouri	6,090,153					1,650,581.70	1,519,778.85		5.4	56.7	1,804,212.95	74.9	2,766,161.20
Montana	3,719,874					3,486,487.61	3,306,487.61	100,000.00	9.4	259.3	137,493.00	13.4	275,893.39
Nebraska	3,914,481	43,132.00	39,210.94		18.2	2,712,212.78	1,988,005.06	108,538.00	30.9	234.1	819,843.36	66.3	1,067,421.64
Nevada	2,909,387					527,623.97	527,623.97		19.3	81.6	621,316.17	79.7	1,760,446.86
New Hampshire	954,919					439,426.36	406,183.50		15.5	7.9			548,735.50
New Jersey	3,065,137					327,297.82	327,297.82		8.6	6.1	28,948.83	.5	2,708,890.35
New Mexico	2,896,467					1,776,445.05	1,776,445.05		17.4	174.2	718,644.85	62.7	401,377.10
New York	10,830,099					8,130,519.00	7,827,060.00	300,000.00	8.2	174.9	1,993,650.00	23.1	1,009,389.00
North Carolina	4,761,147					803,595.81	401,797.95	401,797.86	29.9	94.8	1,123,833.23	158.3	3,235,515.82
North Dakota	2,902,224					872,509.98	872,509.98		31.6	359.3	1,243,530.25	343.8	786,183.77
Ohio	6,968,066					3,324,120.00	3,324,120.00		26.1	88.1	3,015,590.00	62.6	628,356.00
Oklahoma	4,608,399					1,775,719.78	1,775,719.78		3.6	114.4	1,807,422.99	99.8	1,025,256.23
Oregon	3,053,448					1,789,001.67	1,740,702.17		19.0	106.6	1,024,610.70	61.9	288,135.13
Pennsylvania	5,757,978					533,810.98	533,810.98			13.2	2,879,699.67	78.4	2,344,467.35
Rhode Island	999,354					952,043.50	952,043.50		14.7	19.8	42,490.08	.7	4,820.42
South Carolina	2,729,583					715,738.71	713,009.09	2,729.62	5.3	89.8	519,210.42	59.4	1,497,363.49
South Dakota	3,005,739					1,112,298.15	1,077,368.55	34,929.60	37.3	181.5	868,156.17	104.7	1,060,214.28
Tennessee	4,246,309					776,289.69	485,864.15	290,425.54	12.6	14.3	719,905.69	42.9	3,040,539.16
Texas	12,122,012					2,959,818.68	2,253,616.65		9.0	286.3	2,691,190.09	330.0	7,177,205.26
Utah	2,097,354					1,448,385.26	1,448,385.26		53.7	163.6	172,799.35	3.1	476,169.39
Vermont	931,919					611,678.48	611,678.48		13.4	29.0	91,944.79	9.2	228,295.73
Virginia	3,708,379					598,754.92	581,572.05	17,182.87	7.6	25.8	1,252,749.25	50.3	1,874,057.70
Washington	3,057,934					1,153,446.30	1,150,089.48	3,356.82	24.4	50.9	682,589.85	25.3	1,225,254.67
West Virginia	2,013,405					1,321,306.32	1,321,306.32		22.0	58.6	459,853.05	13.7	232,245.63
Wisconsin	4,862,441					2,564,447.01	2,542,947.01	21,500.00	34.1	109.1	422,745.42	29.3	1,896,748.57
Wyoming	2,250,663					1,773,022.95	1,629,300.00	60,000.00	21.4	355.1	324,885.99	76.0	296,477.01
District of Columbia													
Hawaii	1,683,956					87,001.76	43,500.88	43,500.88		5.1	157,010.70	5.1	1,483,444.42
TOTALS	185,807,671	43,132.00	39,210.94		18.2	68,449,063.35	62,784,431.65	3,045,505.30	17.7	4,541.3	42,243,505.80	2,935.8	80,740,522.61

CURRENT STATUS OF U.S. PUBLIC WORKS ROAD CONSTRUCTION
AS PROVIDED IN TITLE II, SECTION 204 OF THE NATIONAL INDUSTRIAL RECOVERY ACT

CLASS II—PROJECTS ON EXTENSIONS OF THE FEDERAL-AID HIGHWAY SYSTEM INTO AND THROUGH MUNICIPALITIES

AS OF OCTOBER 31,1933

STATE	PUBLIC WORKS FUNDS ASSIGNED FOR CLASS II PROJECTS IN MUNICIPALITIES	COMPLETED				UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION		BALANCE OF PUBLIC WORKS FUNDS AVAILABLE FOR NEW CLASS II PROJECTS
		Total cost	Public works funds	Regular Federal aid	Mileage	Estimated total cost	Public works funds allotted	Regular Federal aid allotted	Percentage completed	Mileage	Public works funds allotted	Mileage	
Alabama	2,092,533										119,619.43	6.2	1,972,913.57
Arizona	781,794					11,976.30	11,976.30		8.4	1.0			769,817.70
Arkansas	1,687,084					17,350.27	9,963.18	7,387.09	10.0	.1	207,534.15	7.0	1,469,586.67
California	3,901,839					125,384.62	112,319.65		3.6	1.9	274,909.28	3.4	3,514,610.07
Colorado	1,718,633					105,469.21	105,469.21		62.6	3.0	132,295.57	3.1	1,480,868.22
Connecticut	802,407					369,505.30	369,505.30		1.9	3.2	237,835.98	2.0	195,065.72
Delaware	454,772					185,821.40	185,821.40		14.0	2.0	13,542.50		255,408.10
Florida	1,307,959					139,270.42	76,598.73	62,671.69	1.3	2.9	150,901.19	2.8	1,080,459.08
Georgia	2,724,620										12,325.93	.5	2,712,294.07
Idaho	1,121,562					39,947.35	39,947.35		7.5	3.0	14,616.01	.9	1,066,998.64
Illinois	6,877,199												6,877,199.00
Indiana	4,818,165										24,444.60	.4	4,793,720.40
Iowa	2,815,585					466,173.76	438,350.00		37.0	12.6	477,500.00	14.3	1,899,735.00
Kansas	2,522,401					23,085.32	23,085.32		8.7	.4	73,830.32	6.8	2,425,485.36
Kentucky	2,029,687										31,123.23	1.5	1,998,563.77
Louisiana	1,457,148					264,717.31	264,717.31		16.2	3.7	141,679.31	7.4	1,050,751.38
Maine	842,479					410,082.40	410,082.40		21.2	8.7	50,292.64	2.1	382,103.96
Maryland	891,132					16,788.76	12,638.76		7.9	.6			878,493.24
Massachusetts	4,136,382					385,758.23	339,511.37	40,000.00	15.6	5.1	1,202,687.05	3.8	2,594,183.58
Michigan	4,457,679					273,520.00	273,520.00		59.2	5.9	179,150.00	2.5	4,005,009.00
Minnesota	3,410,102					972,113.85	972,113.85		35.9	48.3	457,127.95	10.7	1,980,860.20
Mississippi	1,744,669					27,687.80	15,228.30	12,459.50		1.8	63,040.23	2.2	1,666,400.47
Missouri	3,045,077					532,146.89	524,278.41		7.4	4.0	253,602.45	4.8	2,267,196.14
Montana	1,859,937					5,275.14	5,275.14		37.9	.3	337,737.24	10.8	1,516,924.62
Nebraska	1,957,240	3,656.08	3,656.08		1.3	448,863.57	448,160.17		16.5	11.5	120,398.50	4.8	1,385,025.25
Nevada	500,051					50,304.27	50,304.27		77.5	1.2			449,746.73
New Hampshire	477,460					26,790.69	20,000.00		20.0	.3	66,313.99	1.5	391,146.01
New Jersey	3,217,442					671,930.61	671,930.61		16.8	5.4	1,349,899.25	7.7	1,195,612.14
New Mexico	1,448,234										234,312.35	5.4	1,213,921.65
New York	7,837,865					2,722,830.00	2,721,530.00		6.1	25.5	2,936,850.00	16.2	2,179,485.00
North Carolina	2,380,573					81,177.36	81,177.36		20.9	4.5	34,177.12	6.9	2,265,218.52
North Dakota	1,451,112					15,572.15	15,572.15		83.5	4.8	146,818.39	5.9	1,288,721.46
Ohio	4,645,378					806,110.00	716,135.00		8.1	9.0	463,400.00	6.6	3,465,843.00
Oklahoma	2,304,200					25,131.78	25,131.78		67.6	1.7	196,768.60	4.9	2,082,299.62
Oregon	1,526,724					190,977.53	190,977.53			4.0	90,442.00	2.1	1,245,304.47
Pennsylvania	5,416,051					130,791.78	130,791.78			3.5	1,053,237.00	21.6	4,232,022.22
Rhode Island	499,677												499,677.00
South Carolina	1,364,791					29,263.72	28,858.71	405.01		3.7	63,717.66	6.7	1,272,214.63
South Dakota	1,502,870					119,000.23	119,000.23		16.8	7.3	140,903.35	7.0	1,242,966.42
Tennessee	2,123,155					39,051.81	39,051.81		7.7	1.6	8,045.84	.5	2,076,057.35
Texas	6,061,006					97,453.50	96,743.96		3.1	5.0	427,855.00	34.6	5,536,407.04
Utah	1,048,677					418,165.45	407,005.45		40.5	11.3	114,539.25	3.1	527,132.30
Vermont	470,628					67,791.23	66,772.62		4.5	2.2	182,872.63	5.8	220,982.75
Virginia	1,854,189					37,864.96	29,104.47	8,760.49	17.2	1.9	730,589.25	7.2	1,094,495.28
Washington	1,877,571					103,208.31	103,208.31		20.3	4.1	206,258.11	4.3	1,568,104.58
West Virginia	1,342,270					39,929.76	39,929.76		35.1	.4	142,263.00	2.2	1,160,077.24
Wisconsin	2,431,220					709,629.31	709,629.31		29.3	19.8			1,721,590.69
Wyoming	1,125,332					179,583.12	179,083.12		2.2	2.9	40,628.77	2.5	905,620.11
District of Columbia	1,151,081					197,493.65	197,493.65		65.8	1.1	809,275.00	3.5	144,312.35
Hawaii													
TOTALS	113,515,642	3,656.08	3,656.08		1.3	11,580,989.12	11,277,994.03	131,683.78	18.5	241.2	14,015,360.12	254.2	88,218,631.77

CURRENT STATUS OF U.S. PUBLIC WORKS ROAD CONSTRUCTION
AS PROVIDED IN TITLE II, SECTION 204 OF THE NATIONAL INDUSTRIAL RECOVERY ACT

CLASS III—PROJECTS ON SECONDARY OR FEEDER ROADS

AS OF OCTOBER 31,1933

STATE	PUBLIC WORKS FUNDS ASSIGNED FOR CLASS III PROJECTS ON SECONDARY HIGHWAYS	COMPLETED			UNDER CONSTRUCTION				APPROVED FOR CONSTRUCTION		BALANCE OF PUBLIC WORKS FUNDS AVAILABLE FOR NEW CLASS III PROJECTS	STATE
		Total cost	Public works funds	Mileage	Estimated total cost	Public works funds allotted	Percentage completed	Mileage	Public works funds allotted	Mileage		
	$	$	$		$	$			$		$	
Alabama	2,092,533								85,000.00	13.5	2,007,533.00	Alabama
Arizona	625,435										625,435.00	Arizona
Arkansas	1,687,084										1,687,084.00	Arkansas
California	3,901,838				98,864.81	85,117.33	1.2	1.1	344,422.34	10.0	3,472,298.33	California
Colorado	1,718,632				245,000.00	245,000.00	4.5	61.7	50,000.00	12.8	1,423,632.00	Colorado
Connecticut	659,120								211,882.58	3.1	447,237.42	Connecticut
Delaware	454,772										454,772.00	Delaware
Florida	1,307,958				22,500.00	22,500.00	4.4	3.1	572,320.03	22.6	713,137.97	Florida
Georgia	2,320,973										2,320,973.00	Georgia
Idaho	1,121,562				548,089.73	547,177.47	12.6	90.8	80,546.18	3.1	493,838.35	Idaho
Illinois	6,262,223				22,161.15	22,161.15		3.6	29,482.33	3.9	6,210,579.52	Illinois
Indiana	501,892										501,892.00	Indiana
Iowa	2,212,245				515,923.71	491,900.00	3.9	25.6	211,700.00	31.2	1,508,645.00	Iowa
Kansas	2,522,401								417,566.37	35.5	2,104,834.63	Kansas
Kentucky	1,879,340				55,267.35	55,267.35		3.0	1,205,854.04	155.2	618,218.61	Kentucky
Louisiana	1,457,148								352,994.46	8.4	1,104,153.54	Louisiana
Maine	842,479				816,400.00	816,400.00	73.0	93.6	25,336.92	.5	742.08	Maine
Maryland	891,132										891,132.00	Maryland
Massachusetts	527,768				367,127.97	367,127.97	22.9	11.5			160,640.03	Massachusetts
Michigan	3,184,057				20,500.00	20,500.00		.7	39,000.00	5.0	3,124,557.00	Michigan
Minnesota	2,131,314				496,763.45	496,763.45	5.8	71.4	971,582.02	140.9	662,968.53	Minnesota
Mississippi	1,744,669				435,000.00	435,000.00	.7	54.6			1,309,669.00	Mississippi
Missouri	3,045,076				179,520.22	179,520.22		24.5	847,458.55	184.1	2,018,097.23	Missouri
Montana	1,859,937								67,669.25	1.2	1,792,267.75	Montana
Nebraska	1,957,240				379,485.60	377,623.28	1.6	113.6	894,386.09	147.1	685,230.63	Nebraska
Nevada	1,136,479				196,097.57	196,097.57	4.6	14.4	322,364.55	29.9	618,016.88	Nevada
New Hampshire	477,460				250,326.44	250,326.44	3.6	9.2	15,137.24	.5	211,996.32	New Hampshire
New Jersey	63,460								55,753.07	.5	7,706.93	New Jersey
New Mexico	1,448,234										1,448,234.00	New Mexico
New York	3,662,137				2,585,123.19	2,581,423.19	11.3	61.2	783,980.00	15.5	296,733.81	New York
North Carolina	2,380,573				77,758.94	72,477.17	41.4	9.1	810,107.85	61.3	1,497,987.98	North Carolina
North Dakota	1,451,112								46,035.01	10.4	1,405,076.99	North Dakota
Ohio	3,871,148				256,500.00	151,064.90	6.6	1.2	799,500.00	17.2	2,920,583.10	Ohio
Oklahoma	2,304,199										2,304,199.00	Oklahoma
Oregon	1,526,724								344,568.18	58.4	1,182,155.82	Oregon
Pennsylvania	7,716,975				2,048,250.96	2,046,860.00		214.3	3,714,262.00	354.8	1,955,853.00	Pennsylvania
Rhode Island	499,677										499,677.00	Rhode Island
South Carolina	1,364,791				179,000.00	179,000.00		31.5	805,186.38	101.1	380,604.62	South Carolina
South Dakota	1,502,870								12,525.42	3.8	1,490,344.58	South Dakota
Tennessee	2,123,155								449,061.76	56.1	1,674,093.24	Tennessee
Texas	6,061,006				397,518.83	343,700.00	5.8	46.3	1,826,736.09	340.2	3,390,569.91	Texas
Utah	1,048,677				188,701.11	188,701.11	13.8	35.4	233,000.16	11.1	626,975.73	Utah
Vermont	465,026				45,086.38	35,469.13	5.6	4.7	148,098.43	10.8	281,458.44	Vermont
Virginia	1,854,189				175,241.73	175,241.73	12.0	39.5	632,765.93	51.3	1,046,181.34	Virginia
Washington	1,180,362				301,411.30	301,410.70	7.0	23.6	325,400.78	21.0	553,550.52	Washington
West Virginia	1,118,559								231,294.90	10.4	887,264.10	West Virginia
Wisconsin	2,431,220				870,301.81	831,286.53	13.6	60.9	201,965.45	6.7	1,397,968.02	Wisconsin
Wyoming	1,125,332				80,000.00	80,000.00	12.5	13.7	166,759.26	18.1	878,572.74	Wyoming
District of Columbia	767,388				331,406.47	331,406.47	28.1	3.4	140,594.41		295,387.12	District of Columbia
Hawaii	187,106										187,106.00	Hawaii
TOTALS	94,676,687				12,185,328.72	11,926,523.16	12.4	1,127.2	18,472,298.03	1,957.2	64,277,865.31	TOTALS

CURRENT STATUS OF U.S. PUBLIC WORKS ROAD CONSTRUCTION

AS PROVIDED IN TITLE II, SECTION 204 OF THE NATIONAL INDUSTRIAL RECOVERY ACT

SUMMARY OF CLASSES I, II, AND III

AS OF OCTOBER 31,1933

STATE	TOTAL APPORTIONMENT OF PUBLIC WORKS FUNDS	COMPLETED				UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION		BALANCE OF PUBLIC WORKS FUNDS AVAILABLE FOR ALL NEW PROJECTS
		Total cost	Public works funds	Regular Federal aid	Mileage	Estimated total cost	Public works funds allotted	Regular Federal aid allotted	Percentage completed	Mileage	Public works funds allotted	Mileage	
	$	$	$	$		$	$	$			$		$
Alabama	8,370,133					1,019,052.26	560,478.75	458,573.51	3.9	38.1	1,680,390.12	174.4	6,129,264.13
Arizona	5,211,960					1,748,601.37	1,746,447.13		7.8	110.6	787,782.12	59.9	2,677,730.75
Arkansas	6,748,335					538,517.05	278,053.27	260,463.78	1.4	3.6	850,346.66	54.0	5,619,935.07
California	15,607,354					4,920,116.59	4,217,809.75		2.2	139.0	2,216,287.30	90.5	9,173,256.95
Colorado	6,874,530					1,370,195.85	1,370,195.85		27.9	118.8	768,756.66	39.0	4,735,577.49
Connecticut	2,865,740					572,131.02	572,131.02		1.7	6.1	510,099.11	5.2	1,783,509.87
Delaware	1,819,088					584,947.70	584,947.70		28.5	21.7	360,520.50	7.5	873,619.80
Florida	5,231,834					1,542,824.85	858,678.65	684,146.20	10.5	56.8	1,461,049.76	58.3	2,912,105.59
Georgia	10,091,185										594,989.10	23.5	9,496,195.90
Idaho	4,486,249					2,079,744.03	2,075,223.55		16.4	210.3	200,391.90	17.7	2,210,633.55
Illinois	17,570,770					22,161.15	22,161.15			3.6	259,342.23	9.8	17,289,266.62
Indiana	10,037,843					1,174,800.00	1,174,800.00		6.6	46.4	1,243,714.19	35.3	7,619,328.81
Iowa	10,055,660					4,737,704.23	4,463,750.00		27.7	198.4	2,004,600.00	124.0	3,587,310.00
Kansas	10,089,604					394,870.61	394,870.61		6.3	49.1	2,990,255.24	311.8	6,704,478.15
Kentucky	7,517,359					1,177,169.61	1,177,168.61		.3	85.9	2,198,097.07	230.1	4,142,093.32
Louisiana	5,828,591					753,005.33	753,005.33		16.6	22.5	1,708,291.28	40.3	3,367,294.39
Maine	3,369,917					2,028,710.94	2,028,710.94		44.6	130.1	333,175.89	7.2	1,008,030.17
Maryland	3,564,527					173,094.69	159,295.94		7.5	5.4	674,613.95	10.0	2,730,617.11
Massachusetts	6,597,100					1,133,523.06	902,576.85	219,984.24	24.7	29.7	1,621,137.30	21.5	4,073,385.85
Michigan	12,736,227					1,363,470.00	1,363,470.00		39.0	76.1	739,850.00	49.8	10,632,907.00
Minnesota	10,656,569					3,538,166.65	3,538,166.63		32.8	479.0	1,596,773.85	187.0	5,521,628.52
Mississippi	6,978,675					830,923.59	670,028.93	160,894.66	1.8	74.9	280,857.36	27.2	6,027,788.71
Missouri	12,180,306					2,362,248.81	2,223,577.48		5.4	85.2	2,905,273.95	263.8	7,051,454.57
Montana	7,439,748					3,491,762.75	3,311,762.75	100,000.00	9.4	259.6	542,899.49	25.4	3,585,085.76
Nebraska	7,828,961	46,788.08	42,867.02		19.5	3,540,561.95	2,813,788.51	108,538.00	24.7	359.2	1,834,627.95	218.2	3,137,677.52
Nevada	4,545,917					774,025.81	774,025.81		19.4	97.2	943,680.72	109.6	2,828,210.47
New Hampshire	1,909,839					716,543.49	676,509.94		11.2	17.4	81,451.23	2.0	1,151,877.83
New Jersey	6,346,039					999,228.43	999,228.43		14.1	11.5	1,434,601.15	8.7	3,912,209.42
New Mexico	5,792,935					1,776,445.05	1,776,445.05		17.4	174.2	952,957.20	68.1	3,063,532.75
New York	22,330,101					13,438,472.19	13,130,013.19	300,000.00	8.4	261.6	5,714,480.00	54.8	3,485,607.81
North Carolina	9,522,293					962,532.11	555,452.48	401,797.86	30.1	108.4	1,968,118.20	226.5	6,998,722.32
North Dakota	5,804,448					888,082.13	888,082.13		32.5	364.1	1,436,383.65	360.1	3,479,982.22
Ohio	15,484,592					4,386,730.00	4,191,319.90		22.4	98.3	4,278,490.00	86.4	7,014,782.10
Oklahoma	9,216,798					1,800,851.56	1,800,851.56		4.5	116.1	2,004,191.59	104.7	5,411,754.85
Oregon	6,106,896					1,979,979.20	1,931,679.70		17.1	110.6	1,459,620.88	122.4	2,715,595.42
Pennsylvania	18,891,004					2,712,853.72	2,711,462.76			231.0	7,647,198.67	454.8	8,532,342.57
Rhode Island	1,998,708					952,043.50	952,043.50		14.7	19.8	42,490.08	.7	1,004,174.42
South Carolina	5,459,165					924,002.43	920,867.80	3,134.63	4.1	125.0	1,388,114.46	167.2	3,150,182.74
South Dakota	6,011,479					1,231,298.38	1,196,368.78	34,929.60	35.3	188.8	1,021,584.94	115.5	3,793,525.28
Tennessee	8,492,619					815,341.50	524,915.96	290,425.54	12.2	15.9	1,177,013.29	99.5	6,790,689.75
Texas	24,244,024					3,454,791.01	2,694,060.61		8.4	337.6	4,945,781.18	704.8	16,604,182.21
Utah	4,194,708					2,055,251.82	2,044,091.82		47.4	210.3	520,338.76	17.3	1,630,277.42
Vermont	1,867,573					724,556.09	713,920.23		12.2	35.9	422,915.85	25.8	730,736.92
Virginia	7,416,757					811,861.61	785,918.25	25,943.36	8.9	67.2	2,616,104.43	108.8	4,014,734.32
Washington	6,115,867					1,558,065.91	1,554,708.49	3,356.82	20.8	78.6	1,214,248.74	50.6	3,346,909.77
West Virginia	4,474,234					1,361,236.08	1,361,236.08		22.4	59.0	833,410.95	26.3	2,279,586.97
Wisconsin	9,724,881					4,144,378.13	4,083,862.85	21,500.00	29.1	189.8	624,710.87	36.0	5,016,307.28
Wyoming	4,501,327					2,032,606.07	1,888,383.12	60,000.00	19.2	371.7	532,274.02	96.6	2,080,669.86
District of Columbia	1,918,469					528,900.12	528,900.12		42.2	4.5	949,869.41	3.5	439,699.47
Hawaii	1,871,062					87,001.76	43,500.88	43,500.88		5.1	157,010.70	5.1	1,670,550.42
TOTALS	394,000,000	46,788.08	42,867.02		19.5	92,215,381.19	85,988,948.84	3,177,189.08	17.1	5,909.7	74,731,163.95	5,147.2	233,237,020.19

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